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CONTENTS

A Mathematical Theory of Production: Planning & Scheduling, by Melvin E. Salveson 3
Evaluation In a Program to Promote Rating Ability in Time Study Work, by R. O. Swalm 7
Statisites In Time Study, by Robert N. Lehrer & Joseph J. Moder 9
Comments On Statistics In Time Study, by John R. Huffman 11
Mathematical Aspects of Work-Factor Allowances for Simultaneous Standard Elements of Work, by Dickey Dyer 12
A Mathematical Foundation for Industrial Engineering, by Howard P. Emerson 14
A Functional Definition of Industrial Engineering, by E. Paul DeGarmo 18
The Importance of Accounting in Industrial Engineering, by J. W. Caldwell 19
Book Review of "Time Study Fundamentals for Foremen," Reviewed by J. S. Dwyer 25
Book Review of "Methods of Operations Research," Reviewed by Robert M. Eastman 26
The Industrial Engineer in Purchasing, by George E. Hecox 26
Book Review of "Factory Planning & Layout," Reviewed by W. A. Brooks 26
Book Review of "A Manual for Time Study Supervisors," Reviewed by Robert M. Eastman 27
Book Review of "The Fundamentals of Top Management," Reviewed by Robert M. Eastman 27

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President's Message

M. A. PAYNE

Membership Requirements

One of the more confusing issues before the A.I.I.E. at this time is that of membership qualifications. They are of primary importance because of their close relationship to the basic purpose of the Institute. When we state we are an organization of Industrial Engineers, we must in fact be that. Also, having established a purpose for the Institute, the members have to be selected to insure that it will be aggressively pursued.

The purpose stated in the constitution is as follows:

To maintain the practice of Industrial Engineering on a professional status

To foster a high degree of integrity among the members of the Industrial Engineering profession

To encourage and assist education among members of the profession

To promote the interchange of ideas and information among members of the profession

To serve in the public interest by the identification of men qualified to practice as Industrial Engineers

To promote professional registration of Industrial Engineers.

A man, eligible for membership in an organization established to accomplish the above, must have a substantial personal investment in the profession. When he works for the good of the Institute he will be working for his own good. In this singularity of interests, assurance is had that the aims and interests of the Institute will be served.

The problem of establishing qualifications is a problem of determining

(Continued on Page 20)

A Mathematical Theory of Production: Planning and Scheduling

By Melvin E. Salveson[1]

University of California, Los Angeles, and George Washington University

Until recently, there had been essentially two major contributions to theory in planning and scheduling. The first was F. W. Taylor's original recognition of the basic problems, for example [29][2]:

"In most cases, for instance, of a machine shop doing miscellaneous work, in order to assign daily to each man a carefully measured task, a special planning department is required to lay out all of the work at least one day ahead. All orders must be given to the men in detail in writing; and in order to lay out the next day's work and plan the entire progress of work through the shop, daily returns must be made by the men to the planning department in writing, showing just what has been done. Before each casting or forging arrives in the shop the exact route which it is to take from machine to machine should be laid out. An instruction card for each operation must be written out stating in detail just how each operation on every piece of work is to be done and the time required to do it, the drawing number, any special tools, jigs, or appliances required, etc."

The second was Gantt's development of the time-progress chart bearing his name [9], and utilizing a graphic analogue as the central means of scheduling. Most other writings have been essentially descriptions of methods and procedures used by particular firms, or analogue definitions of these functions. None has attempted to move toward a quantitative theory in production. For typical example of those writings, the first edition of *Industrial Organization and Management* [5] defines scheduling as "fitting operations into a logical timetable." This definition, of course, does not provide any quantitative criteria for "logical," such that independent experimenters could be assured of achieving the same results from identical experiments. The second edition [6] defines scheduling in industry by comparing it to scheduling on a railroad network, an obvious analogy, but not a definition of any operational significance or utility. Innumerable other instances of similar analyses and definitions are to be found in the literature.

Inasmuch as scheduling is a mathematical problem of considerable challenge, even to the professional mathematician, the preceding brief survey of the literature is not intended as a criticism of the writers in this field. Rather it is a suggestion to the Industrial Engineering profession that there are large potential contributions of the Mathematics profession to be made in the solution of our industrial problems, of which scheduluing is only one. That the scheduling problem is a 'respectable" and formidable challenge to mathematic is indicated by E. W. Barankin[3] [3] who states:

"Among the problems that Econometrics and Engineering have put to Mathematics, the scheduling problem is one of the most interesting and challenging. It combines a most extensive spread of combinatorial considerations with a continuous parameter, time, in such a way that immediate algebraic intuitions centering around groups of permutations seem always to fail to help toward a solution."

Formal solution of these problems will make important contributions to industrial practice: important among these is that we then shall have a basis for using electronic computing and data handling techniques for their solution in much the same manner that our colleagues in other branches of engineering have been able to use these techniques in the solution of their formally defined problems. This paper reports one engineer's attempt to develop a formal theory of production, with particular reference to planning and scheduling and with suggestions in relation to organization theory and communication and managerial decision making.

Notion of Models

As engineers, we are familiar with physical "models" of various systems, such as of aircraft, ships, etc., which we use to determine experimentally the behavior of some prototype. Here we will be concerned with "Mathematical" and "conceptual" models. Such models also represent a prototype, but by an appropriate mathematical statement, i.e., system of equations subject to those restrictions imposed in the phenomenal world. [2, 7] By inserting appropriate values in the equations of the mathematical model we can compute the response of, or equivalently make prediction on the behavior of the system represented; similarly, by examining a conceptual model under given rules of operations, we can predict qualitatively the prototype's behavioral response. A purely mathematical model is not attempted here due to space and other limitations; however, the value of the conceptual model lies in the frame of reference it offers for analyzing and testing rules, methods, and procedures in the prototype system in relation to their efficiency in achieving optimal managerial decisions in planning and scheduling.

Assumptions

The first requirement of a formal model is a set of self-consistent axioms and postulates and of suitable definitions of the objects of the system. Those presented here are generalized, thus permitting a generalized theory of production, but with special theories obtainable by appropriate simplifications for particular conditions. In relation to production, define, therefore, the following:

Process—A controlled transfer of energy to change the state of a material component of a (production) system (essentially analogous to an operation, but used here in a more generalized sense).

System—The agency for carrying out a process (essentially a machine tool with operator, power supply, attachments, and work piece).

State of Material—The state of a piece of material is defined by its properties in time, space, and form (the first two are obvious and the latter are essentially the usual conventional engineering specification of a commodity).

Commodity—An aggregation of material with specified properties and capable, thereby, of participating in some process or carrying out some useful function.

Processes included here are the usual type, such as fabrication, assembly, set up, transportation, storage, chemical, as well as a null or idle-time process. Mathematically, it will be necessary to classify processes also according to

[1] This paper was prepared while the writer was under contract to the Logistics Branch, Office of Naval Research. It represents a considerable abridgement and revision of a paper "On a Quantitative Method in Production Planning and Scheduling" originally presented at the Logistics Conference, George Washington University, January, 1952, and appearing in full length in **Econometrica**, Vol. 20, No. 4 (October 1952). In addition to the acknowledgements included in that paper, sincere appreciation is expressed to Dr. Max A. Woodbury and to the members of the Industrial Logistics Research Project, University of California, Los Angeles, for their helpful comments and suggestions.

[2] Numbers in parentheses refer to references listed at the end of the article.

[3] Associate Professor of Mathematics, University of California, Berkeley.

"continuous" and "batch" (although in reality neither is encountered in its pure form). Properties are similarly classified, each depending upon the processes which generate them. Commodities are classified here according to "in-process," "desired," and the null commodity, or that produced by the null process. (In order to include set-up of tools, etc., completely assembled systems are included in the category of "desired" commodities, but with zero sales price.)

Assume and denote by the following the data available to the "manager" (a hypothetical organizational intellect) in planning and scheduling:

a. Properties of material by subscript j, $j=1, \ldots, J$.
b. Desired commodities by abbreviated name, P_i, $i=1, \ldots, I$.
c. In-process comodities, P_{ij}, where the name indicates the i'th desired commodity as it exists at the completion of the process generating the j'th property. (In case sequence of generation of properties is not linearly ordered, j' will be used to indicate a particular "state", i.e., set of specified properties).
d. Production systems by subscript k, $k=1, \ldots, K$.
e. Time periods by superscript t, $t=1, \ldots, T$.
f. Prices of comodities, u'_i, where u'_i is a number indicating the price in dollars of the i'th commodity during the t'th period of time (primes are added if the number indicates price of material purchased as inputs).
g. Opportunity prices [28] or rents of production systems, w'_{jk}, where any w'_{jk} is a number indicating the price of the k'th system for its use in generating the j'th property during the t'th period of time.

Expanding the definition of "Commodity", we now may write the "commodity technology matrix", (p_{ij}), in which any p_{ij} is a number indicating the number of units of the j'th property in the i'th commodity. It is axiomatic in relation to these properties that there is a technologically determined sequence or order in which any sub-set of properties must be generated. For example, it is necessary to drill a hole before tapping. Denote this ordering on the set of properties, j, by the symbol $<$, such that

$$\text{"}P_{ia} \overset{T}{<} P \overset{T}{<} \ldots \ldots \ldots \overset{T}{<} P_{ib} = P_i\text{"}$$

states that in Producing P_i, property, a, must be generated at some time earlier than property d, etc. Generation of the last property, b, in this subset equivalently completes the production of the commodity P_i. Partial orderings are indicated by commas between those properties which are indifferent as to sequence of generation.

Expanding the definition of "System", we now may write the "production technology matrix" (r_{jk}), in which any entry, r_{jk}, is a number indicating, for continuous processes, the number of units of time required by the k'th system to generate one unit of the j'th property, or for batch processes, the number of units of time required by the k'th system to carry out one process cycle which generates the j'th property. This representation assumes output as a linear function of scale and of number of times the cycle is carried out, both of which are large simplifications of the computational problem without any loss of accuracy of representation if compensating assumptions are made in definition of a process. In regard to production systems, it is axiomatic that any production system has a limited range of capacities according to its design and construction. Define, therefore, the matrix, (c_{jk}), in which any c_{jk} is a number indicating the dimensions of the j'th restricting property of the k'th system. Then for any commodity, i, with properties, j, the commodity can be processed by the system if, and only if, $c_{ij} < c_{jk}$. For example, if the distance between centers of an engine lathe is ten inches, the work piece can be no longer than that distance.

The Conceptual Model

Now we may write the mathematical equations of the model. In this model, it will be assumed that the "manager" solves these equations in such manner as to maximize dollar profit, Π (or in the general case some other more general utility function). His solutions are expressed through his decision functions as follows:

1. Planning, or deciding
   a. What comodities, i, to make,
   b. How many, x, to make of each,
   c. How to make each of them, i.e., using which system, k, for each i and j.
2. Scheduling, or deciding
   a. When, or at what time, t, to produce each property, j, of each quantity, x, of commodity i.

The Gross Income from material transactions in any production plan and schedule is given by Equation 1:

$$\Theta = \sum_{i,t} (x'_i u'_i - x'_i u'_i),$$

where Θ is the gross income in dollars, and x'_i is the number of units of the i'th commodity produced (and assumed sold) during the t'th production period (and correspondingly for purchases indicated by primes).

The family of technologically feasible schedules is given by Equation 2:

$$\sum_{i,j} f(x'_{ijk})\ p_{ij}\ r_{jk} = T'_k,$$
$$\ldots \quad \ldots \quad \ldots$$
$$\sum_{i,j} f(x^{\tau}_{ijk})\ p_{ij}\ r_{jk} = T^{\tau}_k,$$

subject to:

a. selections in x'_{ijk} consistent with the particular technologically determined sequence of processing for each commodity,

b. all choices in x'_{ijk} satisfying the restrictions, $c_{ij} \leq c_{jk}$,

c. $\sum_{ij} x'_{ij} = \sum a_j x^{\pi}_{ij} = \ldots \ldots \ldots = \sum_{i,j} a_j x^{\tau}_{ij}$, (i.e., a consistent inventory policy)

and where:

d. T'_k is the number of units of time in which r_{jk} is measured which are available during the t'th production period,

e. x'_{ijk} indicates the number of units of the i'th commodity assigned to the k'th production system for generating the j'th property during the t'th period of time.

f. and

$$f(x) \begin{cases} = \dfrac{\{x\}_l}{c} \text{ for batch processes} \\ = x \text{ for continuous processes,} \end{cases}$$

and $\{x\}$ is defined as min. n {intergers n $\ni$ n$\geq$x} and c is the restricting property of the system, usually volumetric, as expressed in multiples of the corresponding property in the work piece. Verbally, $\{x\}$ may be defined as the least intergral number greater than the ratio $\frac{\{x\}_l}{c}$.

The cost of any fabrication is given by Equation 3:

$$\sum_{ijk,t} f(x'_{ijk})\ p_{ij}\ r_{jk}\ w'_{jk} = \Gamma'$$

where Γ' is th ecost of fabrication in dollars. The choices, $f(x'_{ijk})$ are the same in equations 2 and 3. These choices imply some zeroes, i.e., choosing not to produce some commodities during some or all periods. Inasmuch as all processes are real and result in increase in entropy, selections in x'_{ijk} are restricted to non-negative numbers.

The equations 2 and 3 hold essentially only for fabrication types of processes. Processes which involve assemblying several components into an assembled commodity, whether assembly of the usual concept, or of others, such as packaging, etc., require a different type of function to describe conveniently. In such processes, it is theoretically possible to assemble a commodity with n component parts in n! different sequences. However, usually

only one of these sequences is the lowest cost sequence. Such sequence is usually determined by "engineering" analysis relating to the technology of assembly-[4] since full enumeration of all possible sequence is a practical impossibility (e.g. $12! = 479{,}001{,}600$). In turn, the assembly tooling methods are laid out to accommodate this selected sequence. If, relative to this sequence, a particular part is received earlier or later than the desired time, it must be stored until desired for assembly, it must be installed "out-of-position", or it requires storing all of the other adjacent parts until it is received. Any of these alternatives involves a cost in excess of the minimum as determined by the optimum sequence. A function used here to describe this cost in assembly relationship is given by Equation 4:

$$\Phi = \sum_{i,n} A_i \left(e^{(T_{in} - t_{in})\ B_i} + e^{-(T_{in} - t_{in})\ C_i} \right),$$

where A_i is one half the cost in dollars of assemblying the i'th part in accordance with the basic sequence; T_{in} is that, t, at which the n'th unit of the i'th part is *desired* in this sequence, t_{in} is that, t, during which the n'th unit of the i'th part is *scheduled* to be completed in fabrication and available to assembly, and B_i and C_i are empirically determined constants selected to generate a representative cost of assembly with different delivery times of the i'th part. It should be noted that this representation assumes a sort of "static" scheduling; a more realistic, but computationally more unmanageable, method for certain types of assembly would be to consider explicitly all of the feasible assembly sequences allowed by the various members of the family of fabrication schedules, since, for example, a different fabrication schedule would be elected in all probability for minor dependent parts if a major part is to be delayed. This selected function appears to be adequate and representative for assembly of large commodities by an assembly line technique. Others may be used for particular situations.

The net profit (or net utility) realized from the production plan and schedule is given by Equation 5:

$$\Pi_{max} = \Theta - (\Gamma + \Phi)$$

where Π, the profit in dollars, is the objective function whose maximum is sought.

[4] For example, the components of a salt shaker (cap, shaker, and salt) could be assembled, theoretically in $3! = 6$ different sequences. However, it is assumed that this analysis leads to the sequence: shaker, salt, and cap. Intuitively, of course, any other sequence or order is clearly inferior.

These equations and choices represent the major managerial choices in planning and scheduling. The model suggests that, if optimal decisions are to be made, the equations must be solved simultaneously. However as mentioned by Barankin, the problems of formal solution of a very detailed model are now virtually impossible, and require further mathematical research. This may be due to the fact that we as Industrial Engineers have not conveyed the formal nature of our problems adequately to the mathematics profession for its cooperation and contributions. Hence, the rule-of-thumb methods discussed in the introduction are to be expected. However, the conceptual model retains its value as a basis for examining empirical methods for their efficiency in achieving optimal decisions. Such examination we undertake in the next section.

Interpretation of the Model

One of the most striking notions emphasized by the model is that the assumed "intellect" (manager) is in fact a large "data processing" system comprising human, servo, and other components. The managerial functions can be viewed best as concerned with solving certain equations, i.e., making certain choices, in order to optimize some objective function for the firm as a whole. Of immediate interest, also in terms of organization theory, is that it is possible to use much experience in circuit and servo mechanism design to evaluate the efficiencies of different modes of organization, communication, and related methods and procedures. That is, any impedance to the flow of information which introduces a time-lag, any introduction of noise or other distortion to the signal, any restriction of the information needed for choices, any inadequacy in channel capacity, or other condition which inhibits information processing, restrices the optimality of the choices in toto which can be made for the firm. From this perspective, these factors could be tested analytically in advance of their adoption in any firm by examining their effect upon the information processing and decision-making. Similarly, it is possible to examine questions of centralization or decentralization by analysing the amount and kind of information which must be available to the decision maker, the sources of that information, and adequacy of various available communication systems for its transmission, channel capacity of the decision maker, etc. Further, the concept of span of control would be reduced to a problem in balancing channel capacity necessary to handle decisions of varying types with that available under different allocations of decision making responsibility. Such questions as organizing according to product type, functional process, geographic location, or other similar basis can be reconciled according to these criteria. Such techniques of organizational analysis, when developed fully, will represent a considerable advancement beyond the present qualitative criteria such as is now typical of this field. One paper by Simon already has appeared which makes use of servo-mechanism theory in examining the production control function [27]. Other theoretical and empirical studies are warranted. The work of Wiener [33] on servo systems with human components is well known.

Some specific practices are now examined in relation to the model and the foregoing analysis. One universal difficulty in manufacturing appears to be that of coordinating the engineering design (specification of properties) of commodities with the shop's ability to produce. It often is found in such situations that the designs are unnecessarily complex in terms of production requirements, are practically unproducible, or require particular productive facilities when such facilities are overloaded, but others would be satisfactory if designs were changed. The essence of the analysis here indicates that the common information which is required between the design and production engineering departments is the abilities and cost of production facilities to generate the various "properties" which may be specified. Ordinarily these data are recorded now on a very informal and often haphazard basis, and seldom made available on a systematic basis to the design department, such that many designs are not consistent with shop abilities and production costs. A more systematic enumeration of the matrices (r_{jk}) (c_{jk}) and (w_{jk}) would permit design engineering, in fact, to do a more adequate job than is now being done with respect to productibility. Sample studies have indicated that such data are not unduly difficult to compile, and are in fact quite informative to the production department itself in increasing the flexibility and level of loading of the shop, quality of output, etc.

The function of process planning (routing, job order writing or other equivalent term) also can be oriented in the light of the concepts presented here. For example, the manufacturing outline in the usual form contains only one method of processing for each operation, when particularly, in job shops, there are many alternatives. This practice can be shown in relation to the model to restrict the scheduler to a much smaller set of solutions to the equations, and results, therefore, in

many instances in a restriction in the output and profitability of the firm. This gives rise to the problem often referred to as "rerouting". From the perspective of the model, it is seen, in fact, to be a problem in which the data (r_{jk}) are recorded originally and of the method of communication between the planner, the schedule, and the shop. Some firms have recognized this problem for what it is and have taken steps to include in the route sheet alternative production methods particularly for operations in which "bottlenecks" are expected. The preparation of these data in advance of actual delays permits more expeditious rescheduling with improvements in deliveries and levels of machine loading.

The Gantt chart, in one form or another, is now one of the best methods of detail scheduling of operations. In view of the combinatorial analysis it involves [23], it is possible to see quite readily the reason that scheduling is described as "fitting operations into a logical timetable." Equations 2 are, in fact, algebraic expressions of the Gantt chart, but with the explicit integration of the chart and its analyses directly into the totality of the firm's decision making function. Although such integration is accomplished intuitively and approximately by the Gantt chart technique, it seldom is sufficiently explicit to make its full impact on the managerial decision making function. If numerical values were obtained, as with the use of the model, the frequent errors and conflicts of intuition and judgment would be replaced by explicit evaluation or determination of the pertinent constants in the equations and solution for the maximum value of the objective function.

The large scale use of the Gantt chart technique often is found to be unmanageable. This is due in large part to the probabilistic nature of the time standards which are used in its construction. That is, time study engineers now generally select some "representative" value (average, median, or other) [4] for any particular operation they have studied, but do not attempt to generate the statistical parameters which describe such other properties as the variability, reliability, etc., of the data. This is true not only of conventional time studies such as are made in the shop, but also true of elemental-motion-time data systems (for example, in all of [17] there is no statistical analysis apparent of any of the original data or the standards developed on them). This incompleteness in time study practices, together with the lack of a method of stochastic scheduling [16, 22], now results in such almost universal rule-of-thumb methods of shop loading as [20].

> "Shop loading is carried out at our plant by estimating the 'unknown' variables affecting production. This usually specifies an underload factor of 30 percent. If we find by experience that this is too high or too low, we adjust the allowance accordingly."

It is clear that such typical methods are the crudest form of statistical analysis of the variability of the production-rate function, and do not permit of statistically well defined estimates nor of adequate analyses of causes of variation from expected values, (for example, as is the usual practice in regard now to statistical analyses in quality control). In order to develop more adequate methods of realistic (stochastic) scheduling, studies are underway at the University of California, Industrial Logistics Research Project to determine experimental methods of measuring rapidly the necessary statistical parameters and to develop methods of scheduling based upon the use of such parameters. For the former purpose, a chronocorder designed by R. G. Canning[5] and being built will pick up and "remember" all selected motion-time values in one cycle of an operation, punch these values directly into an IBM card at the end of the cycle and then proceed similarly with subsequent cycles. It is to be accompanied in operation by physiological energy conversion measuring devices, for a more logical basis for pace rating, such as suggested by Gomberg [12]. By this method of experiment and data recording, it will be possible to proceed directly from the experiment to the analysis of the data, without intervention of the time consuming procedure of micromotion film analysis. This technique is expected to yield data on variability of time standards and on ratings useful to stochastic scheduling theory and practice. A considerable beginning was made in the direction of developing such data by Abruzzi [1] who first applied modern statistical methods of analysis to production-rate measurement. One possible method of stochastic scheduling would be the use of a Monte Carlo technique [30, 24]; such would permit incorporation of micro as well as macro variables in the production-rate function.

The frequency of perturbation in a schedule is an important parameter also in the determination of the degree of centralization of scheduling that may be achieved. That is, if standards are poorly set, work methods and conditions are poorly standardized, control of maintenance and tooling is loose, or other factors exist which contribute either to an earlier or later than predicted completion of a scheduled operation, it will become necessary to reschedule more frequently in order to solve for the optima under the changing conditions in the shop. In order to make such rescheduling effective, it is necessary to have certain information available to the person responsible for such rescheduling, (such as that suggested by this model) as well as allow him some time in which to make the necessary revisions. Where the number of lots of work-in-process is large and the frequency of the perturbation great, it is impossible, using presently available facilities and techniques, to transmit and process the necessary data to so centralize scheduling. Under such circumstances various techniques are used, of which the more frequent are priority systems and expediters. In the original article [23], a sample situation was shown in which a priority system forces a solution to the equations which is less than optimum. In addition, priorities are not quantitatively related to "capacity to produce" or to a quantitative measure of profitability, and hence, are further defective.

Common sense often requires abrogation of priority rules in order to achieve an obvious economy in production. However, the persons ordinarily making such abrogation, the foremen or expediters, often are inadequately informed or are motivated by incomplete objectives, such that their authority to make such adjustments leads to further inefficiencies. From one perspective, priorities operate as a market mechanism [25][6], but the lack of restraint on adding commodities or piece parts to higher priority classes usually results in an inflation in these classes and a deflation in the value which the priority claims represent, such that they become increasingly ineffective and new classes must be added on top of the existing structure. This increases the uncertainty of the real meaning of their value and tends to reduce further their effectiveness as an allocator of productive time.

The logic of centralization can be shown by likening scheduling to a game of strategy [32] which the firm plays against nature. Inasmuch as decentralization permits selection of strategies by individuals with less than complete knowledge of the strategies available, joint determination of the strategy by these individuals would be necessary to achieve the optimum, especially

[5] Assistant Research Engineer, Industrial Logistics Research Project, University of California, Los Angeles.

[6] This interpretation is due to a suggestion by Professor H. A. Simon, Carnegie Institute of Technology.

(Continued on Page 21)

Evaluation in a Program to Promote Rating Ability in Time Study Work

By R. O. Swalm

Associate Professor of Industrial Engineering, Syracuse University

Most of the techniques of making a time study are relatively easy to master. One that is never easy to master is the technique of rating, or comparing the speed and efficiency of the operator being timed with the speed and efficiency of an operator working at so-called "normal" pace. This paper deals with a technique for training time study men to become more proficient in their rating ability and especially to evaluate the results of that technique.

What is involved in the problem of rating? First, we must define what we mean by normal pace—and here we run head on into one of our major difficulties—for a completely satisfactory definition of normal pace has yet to be offered. Many attempts have been made—for example, in an otherwise excellent film, the Associated American Consultants offer this: "Normal pace can be recognized as being neither immoderately fast nor immoderately slow." Obviously that substitutes the unknown "immoderate" for the unknown "Normal" and defines a point on a scale simply as being the area between two immeasurables. Other definitions are equally vague. Typical are:

"The Normal operator is one qualifying in skill and exerting the effort considered normal for the basic rate of compensation."[1]

"The Normal represents an unstimulated rate of production or effort that should be expected from a fully qualified operator. The fully qualified operator, being considered as one who has been working on a job long enough to know it thoroughly and who possesses normal intelligence with enough education to perform satisfactorily the work assigned to him."[2]

"Normal Pace is that pace which is equivalent to walking on the level at 3 miles per hour."[3]

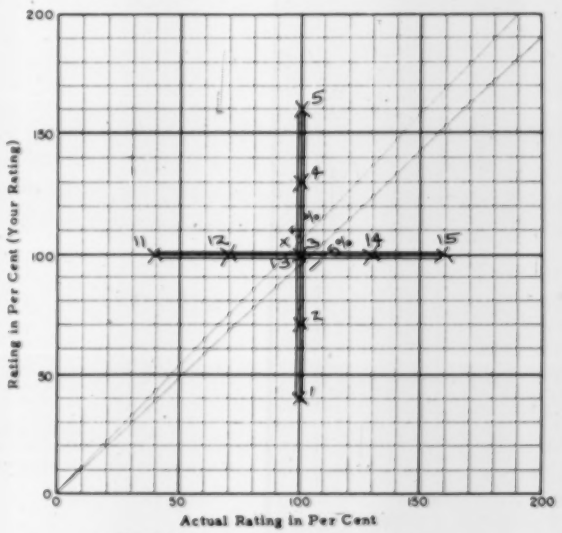
"A person dealing a deck of cards into four equal piles in 0.50 minutes is often considered to be exhibiting normal pace."

The last two represent attempts to be more specific. These are better, but how do you compare the pace of a drill press operator—or a man shoveling sand in a foundry—or a girl assembling nuts and bolts—to the pace of a man walking or dealing cards?

PERFORMANCE RATING SHEET

Job G2 ASSEM. Ratings made by ROS Date 1 FEB. '53

NO.	RATING	ACTUAL	ERROR	
1	40	100	-60	
2	70	100	-30	
3	100	100	0	
4	130	100	+30	
5	160	100	+60	
6				
7				
8				
9				
10				
11	100	40	+60	
12	100	70	+30	
13	100	100	0	
14	100	130	-30	
15	100	160	-60	
16				
17				
18				
19				
20				



SYSTEMATIC ERROR 1-5=0 / 11-15=0 ABSOLUTE ERROR 1-5=36 / 11-15=36 MEAN DEVIATION 1-5=0 / 11-15=0

Fig. 1—Typical form used in evaluating performance rating training.

Indeed, if we could readily arrive at a numerical value for the time per piece while working at normal pace, we would be wasting our time and effort in making a time study. Actually, we can, by means of motion picture analysis, arrive at normal times for some portions of most jobs and we can judge to some degree whether or not an operator who exhibits normal pace on these portions works at about the same relative pace on the remaining portions of the job. This is time consuming and expensive — but it has been found worthwhile to obtain pictures exhibiting normal pace on a number of typical cal jobs in a given plant.[5] Having these, we can make and accurately rate pictures of operators working at other than normal pace on the same jobs. With these pictures, plus a variable speed projector, we can train groups of men in the technique of rating by simply asking them to rate a number of these pictures at intervals, comparing their results with the correct ratings, and continuing this procedure until a satisfactory degree of skill has been obtained. While this technique is not new, it is, unfortunately, far too infrequently practiced. This may be in part due to the fact that, to date, no satisfactory method of evaluating the results of such training has been proposed.

The only known suggestions for numerically evaluating the rating ability of trainees are similar to those first proposed by Barnes.[6] He proposed that, for each reading, the trainee calculate his deviation from the true reading, and then for each series of readings, calculate his Systematic Error,[7] his Absolute Error,[8] and his Mean Deviation.[9] Systematic error is said to "indicate how much too high or too low a person rates on the average"[10]; Absolute error, the average error made (without regard to sign); and Mean Deviation is "an indication of the variability of the ratings of each person."[11] A form (see figure 1) is recommended for recording and summarizing the results of each run. Unfortunately, the

[1]Definition used by Singer Sewing Machine Company.
[2]Northern New Jersey Chapter, Society for the Advancement of Management, "A Progress Report on the Rating of Time Studies," reprinted from "Industrial Engineer," April 1943, p. 1.
[3]Ralph Presgrove, "Dynamics of Time Study," 2nd ed. McGraw-Hill Book Co., Inc., New York, 1945.
[4]R. M. Barnes, "Motion and Time Study," 3rd ed., John Wiley & Sons, New York, 1949.

[5]A technique for developing such secondary standards based on simultaneous, variable speed, motion pictures projection is being investigated at Syracuse University and shows considerable promise. We hope to publish a progress report on this soon.

[6]Barnes, op. cit.
[7]Systematic error is defined as "the algebraic means of the error made"[10]
[8]Absolute error is defined as "the average deviation of the ratings from the actual ratings."[10]
[9]Mean Deviation is defined as "the average deviation of the ratings of each person from his own mean or systematic error."[10]
[10]R. M. Barnes, "Work Measurement Manual," Wm. C. Brown Co., Dubuque, Iowa, 1945.
[11]Ibid.

statistics yielded by these calculations tell little of the true nature of the errors made, nor of the steps to be taken to produce improvement—nor do they indicate the degree of improvement made in subsequent runs. As an extreme example, note that the same value is obtained for each paramater for each of the runs illustrated in Fig. 1 for points 1-5 and points 11-15—although the values are due to diametrically opposite results. In one case the rater saw no variation when the actual variation was great; in the other, he saw wide variation when there was none. This example is obviously carefully selected, and is not typical of actual rating results—but in any event it is impossible to state, for example, whether or not scores of systematic error of 5, absolute error of 10, and mean deviation of 7 represent improvement over scores of systematic error of 2, absolute error of 15, and mean deviation of 10. Nor do these figures give the rater an indication of what the rater should do to improve.

Other sciences have long since discarded these statistics—it is difficult to find them used elsewhere since the first world war. Since implicit in them is the assumption that the trend line is parallel to the true rating line—an assumption which is generally false—they tell us little, and are therefore largely a waste of computational time. But how can they be improved? And still be useful in the shop? The statistician would have a ready answer to the first question. Plot the observed rating against the true rating, calculate, by the method of least squares, the slope of the line of regression and its Y-intercept, and then the confidence limits about the regression line. The first two numbers will completely describe the rater's trend and the last the degree of consistency with which he followed that trend. Such a series of calculations do not, however, satisfy the second criterion. They are impractical for shop use—the average time study practitioner neither understands nor has the time to make them. They represent a step in the right direction—but they must be simplified to be practical.

An obvious step in this direction would be to draw the line that best fits the plotted points by inspection. Some accuracy will be lost—but very little, and much time will be saved. And accuracy is of no value unless it is to be used. Here we want only the general trend—to help us in the future.

Unfortunately, when we come to calculate the standard deviation, we are still in difficulties. We must either scale off each distance from our plotted line, or calculate its value at each rating point, both of which are tedious.

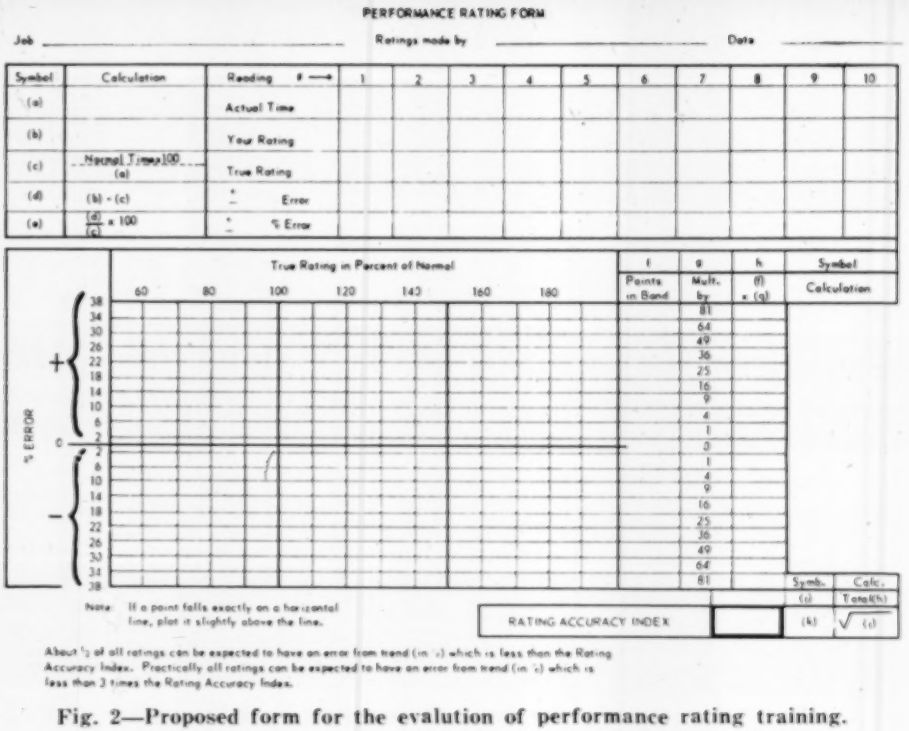

PERFORMANCE RATING FORM
Job
Ratings made by
Date
Symbol
Calculation
Reading # →
Actual Time
Your Rating
True Rating
Error
% Error
True Rating in Percent of Normal
% ERROR
Points in Band
Mult. by
Symbol Calculation
RATING ACCURACY INDEX
Note: If a point falls exactly on a horizontal line, plot it slightly above the line.
About ½ of all ratings can be expected to have an error from trend (in σ) which is less than the Rating Accuracy Index. Practically all ratings can be expected to have an error from trend (in σ) which is less than 3 times the Rating Accuracy Index.

Fig. 2—Proposed form for the evalution of performance rating training.

We give up this calculation with reluctance, however—for the answer is very meaningful. It can predict, within reasonable certainty, just how wide a variation the rater will have from his usual trend—surely valuable information. For example, we know that he will almost always rate within ±2 Standard Deviations of this trend line. We are confident that as the Standard Deviation calculated from successive trials comes down, he is rating more consistently.

But wait—perhaps this leads us to a better answer. We are not interested so much in a man's consistency as we are in his accuracy. Why not compute the root mean square of his errors from the true line rather than his trend line? Would it not be even more meaningful? And the calculations can be, as we shall shortly see, semo-automatic. But in what units should our error be? In percentage points found by subtracting True Rating from Observer's Rating? Experimental evidence[12] shows that this goes up (or down) with actual speed—that a larger *error* is probable at very high speed than at normal. The converse of this—that the rating error becomes lower at lower than normal speeds is not also true; but we seldom, in practice, operate in this range. All things considered, it appears that the most meaningful figures are in percent error in rating. This might be defined as the ratio of the error (with sign considered) to the true rating.

Our final proposal, then, is to make up a work sheet as shown on Fig. 2. The trainee would be asked to draw in his trend line. This would give him the information needed to correct the *trend* of his errors. Then he would count the number of points in each *band*, multiply the number found in each band by the indicated constant, totalize the products, and extract the square root of this total. This gives a function of the root-mean-square of the rating errors, which we define as the rating accuracy index.

Let us examine the function briefly. Since 10 readings are used and the width of each band is 4 percentage points, the rating accuracy index will be ¾ of the estimated standard deviation of an infinite population of similar readings, provided that the mean of this population has an error of zero. This would, of course, be true if the trend line coincided with the zero error line. If this were the case, and if the errors were distributed normally, we could state that, in the long run, about 50% of the errors (in percent of true rating) made by the rater would be within the rating accuracy index—or that about 98% of all ratings would have an error (in percent of true rating) that would be less than three times the rating accuracy index.

If the trend line does not coincide with the zero line, we know, from the theory of the least squares, that the rating accuracy index will be greater

(Continued on Page 24)

[12]Shown, for example, is an unpublished study by Norem, Ribes, Gauthier & Conklin.

STATISTICS IN TIME STUDY

By Dr. Robert N. Lehrer and Dr. Joseph J. Moder

School of Industrial Engineering, Georgia Institute of Technology, based on a paper presented to the Industrial Engineering Division of the American Society for Engineering Education, Annual Convention, 1952

There is considerable difference of opinion among time study men and Industrial Engineers concerning the correct procedures for obtaining a "representative" time value for time study purposes. There seems to be three main schools of thought:

1. The "strength in numbers" school
2. The "selection of the correct value" school
3. The "statistical analysis" school

The "strength in numbers" school has two main options. One group observes a given number of cycles (maybe 10, or maybe 15) for most all situations. They place great faith in an arbitrary number that has no relation to the actual time study situation. These individuals would be quite astonished to know the average error of some of their observed times.

The second group of the "strength in numbers" school places the decision of adequacy with the observer. He must judge when a representative number of observations has been obtained. The observer intuitively analyzes the time values as the study proceeds. Some observers can do a good job by this procedure, but we should be reluctant to place much faith in data obtained in this fashion.

Both of the "strength in numbers" procedures give results of doubtful reliability. The procedures lack objectivity. There is no balance between obtaining sufficient time values but no more than actually needed to obtain reliable data.

The "selection of the correct value" school also has several options. The first group selects a "good" or "representative" time value and disregards all other times. This is done in an entirely subjective fashion. The second group selects time values that result when the observed performance corresponds to a pre-determined level of performance. There seems to be little support for the first procedure. The second procedure may have utility when the observed performance is extremely variable. Both have serious limitations, particularly in view of the probable error of .005 minutes associated with individual stop watch readings.[1]

The "statistical analysis" school is a relatively new approach that is gaining support rapidly, but it has the disadvantage of being only a check on the adequacy of observation after the observations have been obtained. The observations are analyzed by statistical methods to determine reliability, and if the values are not satisfactory then additional observations must be obtained. The analysis can be made with theory based on the normal distribution, or based on "student t" distribution. The variability of the observed times can be used to estimate the number of additional observations required for a given reliability. This, of course, assumes that variability of the initial observations is a true indication of the variability of the succeeding observatoins, which may not be so.

Statistical analysis allows control of the observation error, but it is a bothersome procedure. It provides an excellent means of training the analytical ability of time study observers but it does not allow optimum utilization of observation time, for there is no balance between obtaining sufficient but not excessive observations to assure reliability.

Causes of Variability of Observed Time Values

The variability of observed times within a time study can be due to

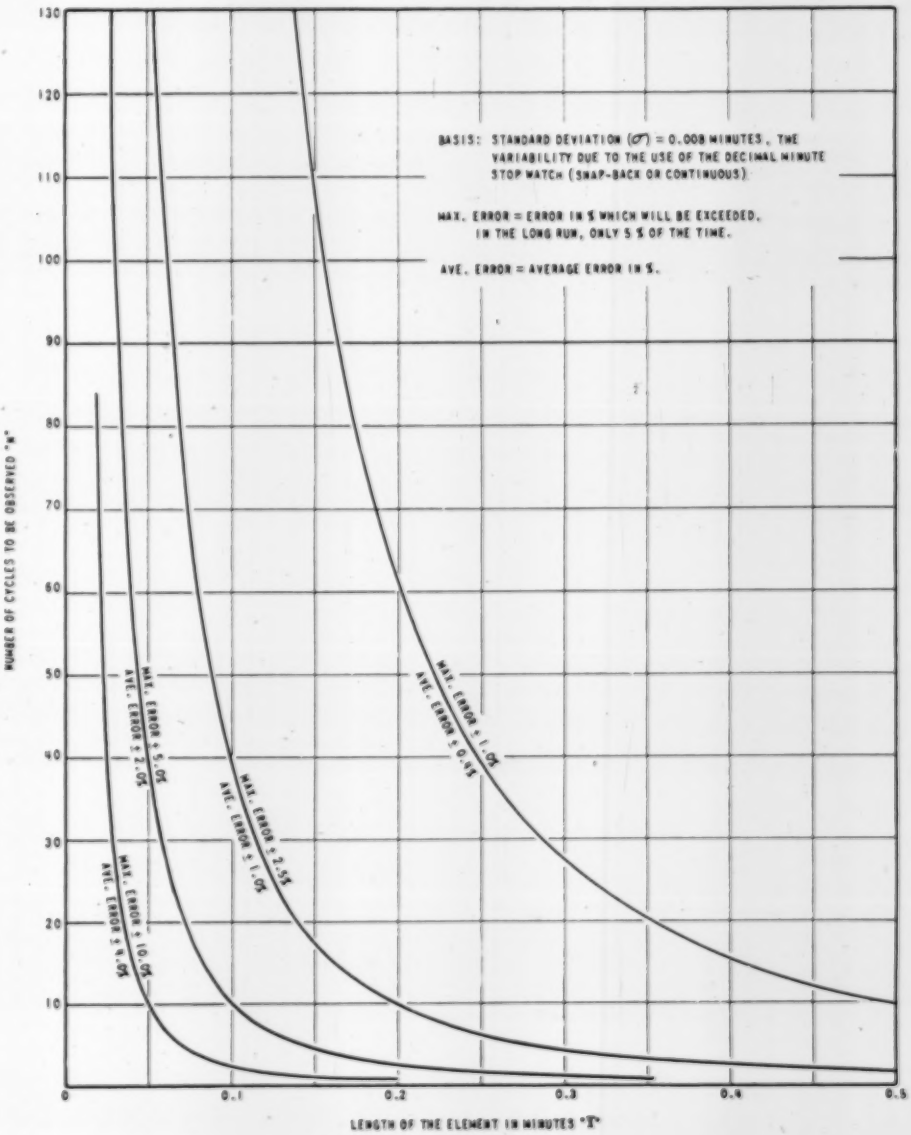


Fig. 1—Minimum number of cycles to be observed to obtain accurate average element times.

[1]See Lehrer, R. N., "How Accurate Is The Stop Watch," Journal of Industrial Engineering, Vol. 3, No. 2.

chance variability or assignable variability. The assignable variability should be eliminated from the study by noting the occurrence of causative acts or circumstances such as malfunctioning of the stop watch, an observable change in job method, an observable change in product quality, missing a watch reading, an obvious change in operator performance, etc.

The chance variability may be caused by either *timing variation*, or *timed variation*. The *timing variation* is due to the characteristics of the timing instrument and the individual using the timing device. The *timed variation* is due to a host of chance happenings in observed performance. Each of these chance happenings is so minor by itself that it is accepted as normal and often is not even detected. These may arise from fortuitous variation in the methods, materials, equipment performance, tools, workplace layout, operator actions, etc.

Prediction of Reliable Time Values

From previous studies,[1] the typical *timing variation* for both continuous and snap-back methods of using the decimal-minute stop watch has been found to have a standard deviation of approximately 0.008 minutes. This standard deviation can be used to predict the minimum number of cycles to be timed to obtain any prescribed degree of confidence and accuracy in the average of the cycles timed. In effect, we can assume that the number of cycles that must be timed in order to control the *timing variation* will be the minimum number of cycles that must be timed. Additional observations are required to control the *timed variation*.

The predictions for the "Minimum Number of Cycles to be Observed to Obtain Accurate Average Element Times" are presented graphically in Figure 1. The curves allow a time study man to determine the minimum number of cycles he needs to observe in order to control the variation "built-into" the watch and the use of the watch. He must decide what level of accuracy is desired, and the approximate time of the shortest element in the job. He can then observe sufficient cycles to have confidence in the control of the timing error.

The predictions presented in Figure 1 are based on the normal distribution since $\bar{X}$'s for samples of 4 or more can be considered as being normally distributed. If the percentage error is based on the sample average, the conventional expression for the normal z can be solved for n, the sample size which will give a specified degree of confidence that the error in the estimate of the mean will not exceed a specified percentage.[2] We have chosen the usual confidence level of 95% and have solved this expression for n for values of 1.0, 2.5, 5.0, and 10.0% error.

An equivalent average error in % has been calculated for these same curves.[3] The average error or mean deviation, as a measure of variation, although inefficient and difficult to handle mathematically, is well understood by most engineers.

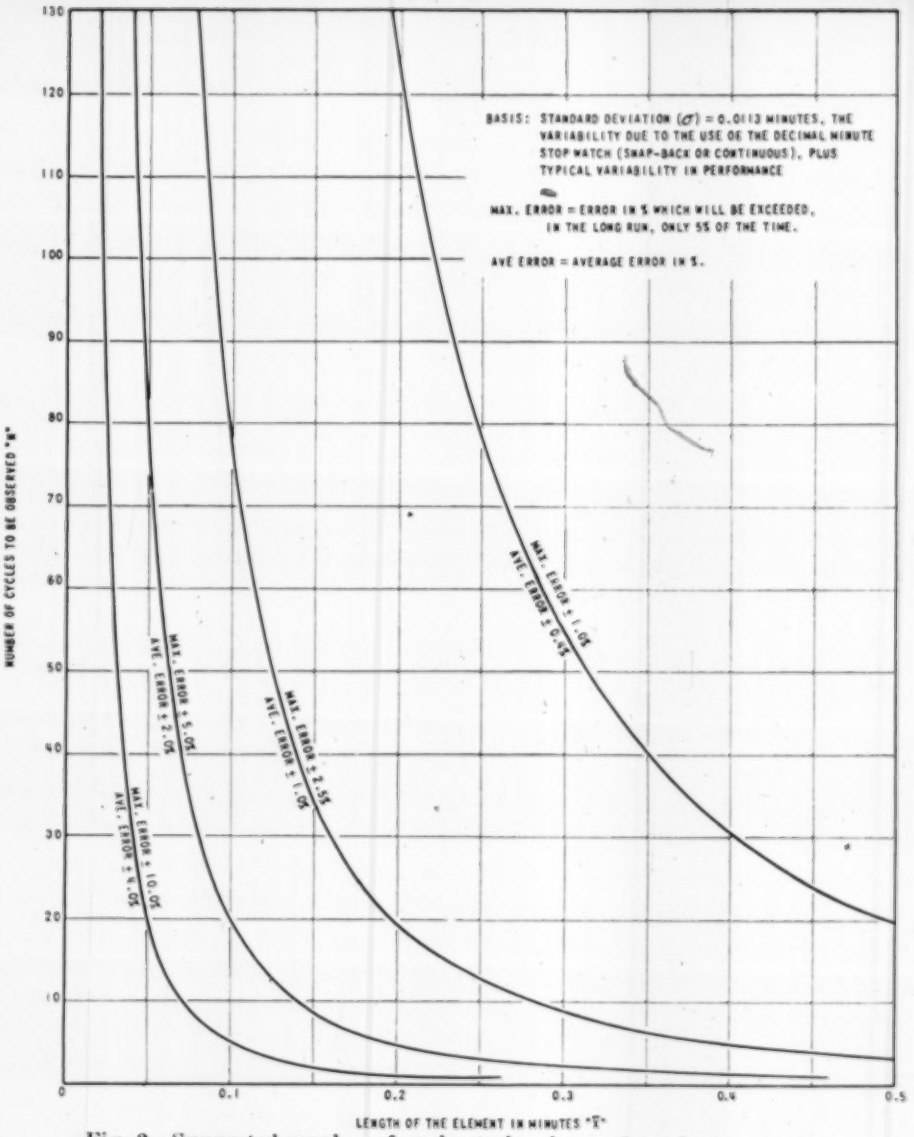


Fig. 2—Suggested number of cycles to be observed to obtain accurate average element times.

In the preceding discussion we have ignored the *timed variation* and have established the number of cycles that must be timed in order to control the *timing variation*. The values obtained from the curves of Figure 1 indicate the minimum number of cycles to be observed. In actual practice the *timed*

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[1] Lazarus, I. P. "The Nature of Stop Watch Errors Among Experienced Industrial Engineers." Master of Science in Industrial Engineering Thesis, Purdue University, 1950.

2/ (1) $Z = \dfrac{\bar{x} - m}{\sigma / \sqrt{n}}$

(2) $\dfrac{100\, Z\, \sigma}{\bar{x}\sqrt{n}} = \dfrac{\bar{x} - m}{\bar{x}}(100)$

$= \%$ ERROR $= K\%$

(3) $n = \left[\dfrac{100\, Z\, \sigma}{\bar{x}\,(K\%)}\right]^2$

3/ A.E. or M.D. $= 0.8\,\sigma_{\bar{x}} = \dfrac{0.8\sigma}{\sqrt{n}}$

A.E. $\% = \dfrac{\text{A.E.}}{\bar{x}}(100) = \dfrac{0.8\sigma(100)}{\bar{x}\sqrt{n}} = \dfrac{80\sigma}{\bar{x}\sqrt{n}}$

Since $\bar{x}\sqrt{n}$ is constant for each of the curves in Figures 1 and 2, the A.E. % is constant and is given by the above formula.

Since $\sqrt{n} = \left[\dfrac{100\, Z\, \sigma}{\bar{x}\,(K\%)}\right]$

variation must also be controlled. The *timed variation* will depend upon the job conditions and the operator performance, and will vary from study to study. A research project is now being initiated at Georgia Tech to investigate the nature of this type of variation for a large variety of job situations. As a first approach, it is reasonable to assume that the *timed variation* is of approximately the same magniture as the *timing variation*. Based on this assumption, the total variation in a series of elemental observations will have a standard deviation of 0.0113 minutes.[4]

A series of curves, similar to Figure 1, based on the standard deviation of the combined *timing variation* and *timed variation* have been computed and are presented in Figure 2 "Suggested Number of Cycles to be Observed to Obtain Accurate Average Element Times." These curves allow a time study observer to determine the approximate number of cycles he needs to observe in order to control both the *timing variation* and the *timed variation*. The observer must decide what level of accuracy is required and approximate the time of the shortest element in the study. He then can determine, by reference to the appropriate curve, the number of cycles he should observe in order to obtain accurate average times.

Conclusions

The curves suggested as tools for the practicing Time Study man should be used with full recognition of the inherent limitations due to the assumptions that were made in their development. If the built-in assumptions are not justifiable in a particular plant situation—then the curves should not be used without modification. Appropriate curves can be constructed to suit the specific conditions of an individual plant or situation.

Some of the assumptions that were made in the development of the proposed curves are:

1. Detectable variations in *timed variation* will not be included in the time study computations.
2. Detectable variation in the *timing variation* will not be included in the time study computations.
3. The values for *timing variation* are based on an investigation conducted by Lazarus. Although this seems to be an excellent research, the data cannot be assumed to be absolutely correct.
4. The Lazarus data groups the performance in timing into average results. In some situations it may be desirable to have curves for individual Time Study men based on their individual facility in stop watch use.
5. The assumption of *timed variation* being equal to *timing variation* may not be absolutely correct. There is strong evidence to indicate that *timed variation* may be a function of the characteristics of the work being performed, the operator being observed, and the organization where the work and observation takes place.

In using the curves presented in this paper, additional basic decisions must be made. These decisions have to do with selection of the appropriate curves for the individual situation. Desirable or acceptable error values must be agreed upon, based on the 95% level of confidence that was used in the development of the curves.

The material presented has been presented in the spirit of helping us do a better job of our time study work by outlining a procedure that guides us in determining when we can expect to obtain reliable time study data. This is only one of the many problems of developing better time study results. The curves and the procedure used to develop them are tools. They must be used within their limitations and only when the inherent assumptions can be justified. If the proposed curves are not suitable for your situation, then develop your own along the general lines that were presented.

Where K% = the error which will be exceeded a specified percent of the time in the long run.

Then $\bar{x}\sqrt{n} = \dfrac{100\,Z\sigma}{K\%}$

and A.E.% $= \dfrac{80\sigma\,(K\%)}{100\,Z\sigma} = \dfrac{0.8\,K\%}{Z}$

For example, if K = 10% and Z = 2, corresponding to 95% confidence, then

A.E.% $= \dfrac{.8 \times 10}{2} = 4.0\%$

4. $\sigma_{Total} = \sqrt{\sigma^2_{timing} + \sigma^2_{timed}} = \sqrt{.008^2 + .008^2} = .0113$ Min.

Comments

By John R. Huffman
Associate Professor of Industrial Engineering, University of Southern California

While I am very much in favor of research to develop rigorous, quantitative techniques for industrial engineering, I believe we should *use* research results with extreme care.

First of all consider the expression:

$$\sigma_{total} = \sqrt{\sigma^2_{timing} + \sigma^2_{timed}}$$

If σ_{timing} is .008(0) minutes, *completely eliminating it* will affect some assumed σ_{totals} as follows:

Assumed Values of σ_{total} ($\sigma_{timing} = .008$)	σ_{total} if σ_{timing} is eliminated	Per Cent Reduction in σ_{total}
.0300	.0288	4
.0200	.0183	9
.0113	.0080	30—
.0100	.0057	43—

This table demonstrates the extreme importance of knowing σ_{timed} or σ_{total} and therefore the importance of the further research mentioned by Drs. Lehrer and Moder.

Assuming — as Drs. Lehrer and Moder do — $\sigma_{timing} = \sigma_{timed}$, consider the .008(0) minute valve for σ_{timing} and the experiment on which it is based. In the experiment, σ_{timed}—i.e., the variability in element time due to the operator—was absent; the element break points were quite clear—a flash of light or a buzz; all watches were checked just prior to use; and finally the laboratory conditions of the experiment practically eliminated any watch reading distractions. The experiment showed that, even under such ideal conditions, the individual observations made by many observers on elements of any length will be distributed as follows:

a. 67+% within ± .008 minutes of the element time
b. 95+% within ± .016 minutes of the element time
c. 99+% within ± .024 minutes of the element time

NOTE: Element time must be accurate to four places.

In the extreme case of a .0500 minute element, the 95% and 99% confidence limits for individual observations would be .034 to .066 and .026 to .074 minutes respectively. Or effectively the observations will include values of .03 and .07 when the actual element time is unchanged from cycle to cycle at .0500 minutes. Intuitively this seems improbable for an element of constant length with a definite break point; some check on intuition is provided by the sigma for automobile braking reaction time—.0013 or .0016 minutes[5].

Are there any possible reasons for the magnitude of σ_{timing}? Yes, it is made up of two components (under the conditions of the experiment): (a) the variability of element mean times from observer to observer ($\sigma_{X\text{-}BAR}$) and (b) the variability of the individual times recorded by an observer (σo). Then for a group of time study men:

$$\sigma_{timing} = \sqrt{\sigma^2_o + \sigma^2_{X\text{-}BAR}} \qquad (2)$$

Obviously there are three very different possible combinations of σo and $\sigma_{X\text{-}BAR}$. In the first of these σo must be constant and small in comparison to $\sigma_{X\text{-}BAR}$. This hypothesis is based on the two well known techniques of reading a time recording instrument with a moving hand:

[5] Lazarus, I. P., "The Nature of Stop Watch Errors Among Experienced Industrial Engineers." Master of Science in Industrial Engineering Thesis, Purdue University, 1950.
[6] Greenshields, B. C., "Reaction Time in Automobile Driving." **J. appl. Psych.**, 1936, 20, 353-58. (Based on 429 people.)

(Continued on Page 25)

Mathemaitcal Aspects of Work-Factor Allowances for Simultaneous Standard Elements of Work

By Dickey Dyer

Business Manager, The WORK-FACTOR Company, as presented to the American Institute of Industrial Engineers, National Convention, 1951

It is the purpose of this paper to discuss the technical and mathematical aspects of the changes in time when motions or elements of work are performed simultaneously by the right and left hands.

This consideration has been a subject of much discussion in the industrial engineering field for years. When the original WORK-FACTOR research had reached the stage of deciding how simultaneous elements should be treated, it was found that the information already available in technical literature was inconclusive. Consequently, the available data was supplemented by continued WORK-FACTOR research.

The first step was to review all previous motion-time measurements and to segregate all observations and resulting evaluations into four classes:

Time for motions made by right hand, left hand idle.
Time for motions made by left hand, right hand idle.
Time for motions made by right hand, left hand moving.
Time for motions made by left hand, right hand moving.

Since most of the previous observations had been made on actual factory operations, it was found they were divided in number. About 57% of the observations were for the right hand and 43% for the left hand. Approximately 69% had been made when both hands were in motion.

Tabulation by the four categories showed that the motion-times for each were identical with the others. This was an unexpected result. Since it had already been reasonably well established that simultaneous right and left hand operations actually require greater time than do non-simultaneous motions, it was obviously necessary to conduct a special investigation to reconcile or correct the two findings.

This was one of the types of problem which required laboratory rather than factory investigation. Over 40 types of separate experiments were conducted. Some of the significant results are worth outlining.

Basic Findings

One of the earliest conclusions was that "individual motions" behaved differently than do "elements of work," i.e., sequences of motions which form therbligs or WORK-FACTOR standard elements. This is an important distinction and should be kept in mind throughout the following discussion.

1. For practical time-study purposes, it was found that the time for right hand motions is essentially the same as for left hand motions. (From a technical standpoint, we should speak of "preferred hand" and "non-preferred hand.")

This result was somewhat different from that of others who, at about the same period, had made comparisons between movements made by the "preferred" and "non-preferred."

In recent years the WORK-FACTOR findings have been substantiated by others. About 1945 to 1947, the Applied Psychology Laboratory of The Johns Hopkins University was making observations on motion-times as part of special Air Force contracts. The findings are reported in "Applied Experimental Psychology" by Chapanis who states that . . . time for motions made by the preferred hand do not seem to prove much different from that for motions made by the non-preferred hand. In fact, there is some evidence to indicate that the non-preferred hand moves faster than the preferred hand.

In May, 1951, the University of Wisconsin reported research showing that right hand operators moved both hands at about the same speed. They found that left handed persons could move their favored hand faster than their right hand.

2. Original WORK-FACTOR study also showed that individual motion-times are not essentially different when performed by one hand with the other idle or when performed with both hands in motion.

For four place timestudy accuracy, it was found that there was no appreciable difference between single and simultaneous motions when:

a. The hands were moving toward or away from one another in a right-left symmetrical pattern.
b. The hands were moving in the same direction away from or toward the body.

A slight increase was apparent when the hands moved in opposite directions away from and toward the body, but again the increase was too small to require any special addition to WORK-FACTOR select time.

3. When sequences of motions rather than individual motions were studied, an obvious and substantial increase was found for simultaneous elements. Depending upon the specific conditions, this increase ranged from 15% to 50% and more. It was greatest where the sequence involved the most complicated sequences — especially complex grasps from random piles and complicated assemblies.

At first this seemed contrary to the conclusion that individual motions could be made equally fast with one hand or with both. In other words, "How could the total time be greater than the sum of all of the individual parts?"

Re-evaluation of the data soon revealed that a portion of the answer rested on the fact that a set of motions, when performed simultaneously, were considerably different than when performed individually.

In other words, when a sequence of motions was changed from a single hand job to a two hand job, many physical characteristics changed so that a new motion pattern was involved. Usually, this new pattern required more time than the single handed pattern.

4. Comparative analyses showed that the following measurable changes could take place in simultaneous operations:

a. Moving distances could increase in order for hands to perform motions without collisions with each other.
b. Some actions could not actually be performed simultaneously because of physical or visual restrictions.
c. The number of fumbling, separating and aligning motions usually increased because of the division of vision and attention.

All of these characteristics were observable and measurable in terms of WORK-FACTOR tables and rules. In most cases, they accounted for a substantial portion of the time difference between the single and simultaneous sequences. For example, consider the following simple operation:

Single hand sequence (right hand only picks up and assembles switch to slot)

1.	Reach to switches	A10D	61 units
2.	Grasp switch (½"S-Solid-Visual)	Table	32 "
3.	Move switch to inpection point	A10D	61 "
4.	Inspect switch for polarity mark	Fo+1Pt	50 "
5.	Pre-position switch end for end	3F1—50%	24 "
6.	Move switch to mounting slot	A3SD	41 "

7.	Assemble switch to slot (.5"T—.9R)	Table	57	"
8.	Index (a part of #7)	A1S	26	"
9.	Release switch	½ F1	8	"
	Total Select Time		.0360	Min.

Simultaneous sequence (right and left hands each pick up and assemble switches to slots)

1.	Reach to switches	A10D	61	units
2.	Grasp switches * (½"S-Solid-Blind)	Table	40*	"
3.	Move switches to inspection point	A10D	61	"
4.	Inspect 1st switch for polarity mark	Fo + 1Pt	50	"
5.	Inspect 2nd switch for polarity mark*	Fo + 1Pt	50*	"
6.	Pre-position 1st switch end for end	Simo#5		
7.	Pre-position switch end for end	3F1—50%	24	"
8.	Move stitches to mounting slots	A3SD	41	"
9.	Assemble switches to slots—6" apart* (.5"T—.9R—5"TD)	Table	66*	"
10.	Index (a part of #9)	A1S	26	"
11.	Release switches	½ F1	8	"
	Total Select Time		.0427	Min.

***Actual changes in motions due to simultaneous action but not including "Simo Allowance."**

In this simple operation, the recognizable increases amount to (.0427—.0360) or .0067 minutes. This is an increase of about 18.6%.

5. Such recognizable increases in work did not always account for the actual increase in time. The discrepancy seemed to increase in proportion to the complexity of the sequence, especially where there was a large number of grasps from random piles, pre-positions or assemblies.

The exact reason for this discrepancy remained a mystery for many months until it was accidentally noted that the greatest discrepancies occurred where the sequences involved motion patterns which varied from cycle to cycle. For example, involving: pre-positions every other cycle, alignments which might vary from zero to three depending upon the chance accuracy of the preceding move, or separates or fumbles which could easily change with each pick up.

Following this discovery, it was almost immediately concluded that the differences were due to the difficulty of coordinating the hands and keeping them in rhythmic phase with each other. In other words, we generally expect that an operator will keep the two hands in a more or less fixed phase with each other. If both hands are picking up and assemblying objects simultaneously and in a specific cycle and one hand has a 3F1 pre-position while the other hand has no pre-position, the hands are immediately thrown out of phase by .0048 minutes. If one or two other variables happened in the one hand and not the other, the phase shift could become appreciable, so that one hand might be reaching while the other was moving, whereas they had formerly moved and reached together.

A few exceptional operators can work through shifting phases. We do not expect the average experienced operator to do so. Therefore, wherever variable motion sequences occur, it is expected that the operator will pace himself to keep in phase with the hand having the most difficulty. Here the term "variable motion sequence" is used to define any element involving motions which occur on an average, random or percentage bases. WORK-FACTOR Standard Elements of Work which involve such variables are: Complex Graps, Pre-Positions, and Assemblies.

6. Based upon these findings, it was evident that some additional compensation must be made for simultaneous variables. Today, we call such additional compensation a "simo allowance."

The question of how much "simo allowance" was yet unanswered, although the problem was fairly well understood.

Mathematical Aspects

Various simo allowance measurements were made, but the problem was not finally resolved until 1940. At that time, Mr. Paul Taub, then at RCA Victor, was asked to analyze the problem from a purely mathematical standpoint. A few elementary calculations soon clarified the effect of simo sequences.

In order to reconstruct the mathematical solution, we will first review the fundamental laws of the mathematics of probability.

Theorem I—If P is the probability that an event will occur, then 1—P is the probability that the event will not occur.

Theorem II—If P_1 is the probability that event A_1 will occur, and P_2 is the probability that event A_2 will occur, then $P_1 P_2$ is the probability that event A_1 and event A_2 will occur together.

Theorem III—If P_1 is the probability that event A_1 will occur, and P_2 is the probability that event A_2 will occur, then $P_1 + P_2$ is the probability that at least one of the events A_1 or A_2 will occur.

Theorem IV—If P is the probability that an event will occur, and M is a magnitude associated with the event when it does occur, then P M is the mathematical expectancy (effective mangitude).

Let . . .

P_1 = Probability of occurrence of a variable event in one hand.

M_1 = The time for the variable event in that hand when it does occur.

P_2 = Probability of occurrence of an independent variable event in the opposite hand.

M_2 = The corresponding time for the event.

Then by Theorem II, the probability that both variables will occur simultaneously in the right and left hands is:

$$P_1 P_2$$

By Theorem III, the probability of P_1 is:

P_1 = (Probability of P_1 only) + (Probability of P_1 and P_2 simo)

$P_1 = P_1$ only $+ P_1 P_2$

The probability of P_1 occurring only is:

P_1 only $= P_1 - P_1 P_2$

Also:

P_2 only $= P_2 - P_1 P_2$

By Theorem III, the probability that an event will happen in either the right hand, the left hand, or both is:

$$P_x = P_1 + P_2 - P_1 P_2$$

Since P_1 and P_2 are always equal to or less than 1, it follows that:

$$P_1 \geq P_1 P_2 \leq P_2$$

Therefore—

$$P_1 \leq P_x \geq P_2$$

Which means that the total probability is greater than either of the individual probabilities. As a simple example: Assume that the right hand had a 50% pre-position and that the left hand has a 50% pre-position. Then according to the above:

Probability that both right and left hands pre-position =

$$P_1 P_2 = .5 \times .5 = .25$$

Probability that right hand only pre-positions =

$$P_1 - P_1 P_2 = .5 - .25 = .25$$

Probability that left hand only pre-positions =

$$P_2 - P_1 P_2 = .5 - .25 = .25$$

Probability that at least one hand pre-positions =

$$P_1 + P_2 - P_1 P_2 = .50 + .50 - .25 = .75$$

Probability that neither hand pre-positions =

$$1 - .75 = .25$$

If M_1 is the time for a variable event when it does occur, then $P_1 M_1$ is the average time which is normally recorded in a non-simo timestudy analysis. Similarly, $P_2 M_2$ is the average time for a variable event in the opposite hand. The overall average time when done simo is:

$M_x =$ (Average time for hand having largest time when event does occur) + (Average time for opposite hand when event occurs in that hand only)

$= P_1 M_1 + (P_2 - P_1 P_2) M_2$ WHEN $M_1 > M_2$

$= P_2 M_2 + (P_1 - P_1 P_2) M_1$ WHEN $M_1 < M_2$

As above it can be shown that

$$P_1 M_1 \text{ or } P_2 M_2 < M_x > P_1 M_1 \text{ or } P_2 M_2$$

In non-mathematical language this means that the total average time is greater than either of the individual average times.

The actual increase in time over the greatest single hand time is given by the following:

(Continued on Page 24)

A Mathematical Foundation for Industrial Engineering

By Howard P. Emerson

Professor and Head, Industrial Engineering Department, University of Tennessee.

Based on a Paper Presented to the Industrial Engineering Division of the American Society for Engineering Education, Annual Convention, 1952.

Engineering has always been built on a foundation of mathematics and the basic sciences.

The trend today is toward greater use of mathemtics. The Committee on Adequacy and Standards of Engineering Education of ASEE recently concluded that "the greatest potential for future development in science and technology is to be found in mathematics."[1] Engineering fields other than Industrial Engineering are finding growing need for a better foundation in mathematics and for mathematical courses higher than calculus.

For example, in the Southeast, curricula are beginning to be influenced by three big projects, the atomic energy development at Oak Ridge, the Arnold Engineering Development Center at Tullahoma, Tennessee, and TVA with its regional electric power system. All of these projects maintain teaching or research relationships with the engineering colleges of the Southeast. The mechanical engineers are finding a need for higher mathematics for wind tunnel and jet propulsion calculations, the chemical engineers need higher mathematical analysis for atomic reactor design, and the electrical engineers have long required courses in differential equations since rates of change dominate their fields of study. (See Table I for one comparison of math courses for various engineering groups.)

What about the Industrial Engineers? Do I. E. students already get enough mathematics or will Industrial Engineering follow the path of other engineering fields which also started with practical, rule-of-thumb methods but have become more and more dependent upon mathematics?

This program today on "Mathematical Analysis in Industrial Engineering" is intended to explore this question. In preparation for it one of the participants made a significant discovery—that it was hard to find Industrial Engineering applications of general mathematics, other than arithmetic and algebra, but further that there are "few applications of mathematics to industrial engineering problems that do not involve some aspects of statistics."

This discovery raises two points for consideration:

1. What present or future Industrial Engineering problems require mathematics in their solution and what are the mathematical techniques which the Industrial Engineer needs to solve them?
2. If most of the applications of mathematics are found to involve some aspects of statistics, is not this the logical field of specialization for Industrial Engineering?

[1] S. C. Hollister, C. S. Crouse, L. F. Grant, and M. D. Hooven, "Report of Committee on Adequacy and Standards of Engineering Education," **The Journal of Engineering Education**, 42: 249-254, January 1952.

Table I

MATH COURSES HIGHER THAN CALCULUS FOR ENGINEERING STUDENTS AT THE UNIVERSITY OF TENNESSEE 1952-53[1]

Civil Engineering:	Upper Division Math courses may be elected by the student.
Chemical Engineering:	Differential Equations and Advanced Calculus are major electives taken by over half the students, required of Nuclear Processes Group.
Electrical Engineering:	Elementary Differential Equations, required of all students. All graduate students will take an upper division math series, Applied Mathematics for Engineers, 9 quarter hours.
Engineering Physics:	Differential Equations and Advanced Calculus (9 quarter hours) or Introduction to Analysis required.
Mechanical Engineering:	The new "unified" math course is considered to provide enough differential equations for the course in Mechanical Vibrations, which previously had a Differential Equations prerequisite. All graduate students will take an upper division math series, Applied Mathematics for Engineers, 9 quarter hours.
Industrial Engineering:	Introduction to Mathematical Statistics (3 quarter hours). A second quarter is optional. These are followed by I. E. courses in Quality Control.

[1] Examination of curricula at various other engineering colleges throughout the country indicates that the above table is typical in the following respects:
a) All Electrical Engineering but few other curricula require Differential Equations.
b) Emphasis on mathematics higher than calculus does not show up in published undergraduate curricula. If present, it appears in recommendations to students for elective courses and in requirements for higher degrees, as illustrated in the above table.

Mathematics Course Needed

Based on the present list (Table II) how much mathematics would be needed in the undergraduate or graduate curriculum?

Most of the conventional mathematical techniques listed in this table, with the exception of statistical mathematics, are probably included in what students get now. At least this is what we found at the University of Tennessee, where our recent review of mathematical requirements common to all engineering fields suggested that few new topics needed to be added in the existing subject matter. Our engineering faculty adopted a requirement which goes into effect next fall, of 5 hours each quarter in mathematics for the first two years, a total of 30 instead of 24 quarter hours in a common unified course for all engineering students. This unified course starts with differential calculus in the second week of the freshman year and ends with a brief introduction to differential equations. It is hoped that this will answer the objection of all departments requiring advanced work in mathematics that poor preparation limits performance in higher mathematics courses.

Later courses can be added on such an expanded two year mathematics foundation, if they become desirable. What would be such higher courses for the Industrial Engineer? One might be matrix algebra, useful in solving simultaneous equations and reaching decisions on optimum situations in-

volving many variables. Differential equations may not be necessary since most of those Industrial Engineering phenomena involving rates of change can be handled by integral calculus. In the new field of cybernetics, involving substitution of mechanical for human brains in the form of computing machines, the Industrial Engineer already uses IBM punch card equipment and automatic calculating machines of ten digits, and these may be adequate for some years to come. In another new field, operations research, statistical mathematics comes into play.

Statistical Mathematics

The major exception not covered adequately in the basic two year mathematics course for engineers is mathematical statistics. Engineers have lagged behind in using statistical methods. Nearly every other profession has made use of them. If Industrial Engineering follows the trend of other engineering fields in requiring advanced mathematics in undergraduate or graduate work, I believe its field of specialization will be that of mathematical statistics. Statistical methods have already opened up new opportunities. They have brought striking results in quality control. But control of quality is only the beginning of the applications of mathematical statistics to manufacturing and production. On the program this afternoon there is to be an analysis of time study procedures as affected by statistical methods. In fact statistical methods have been used to discredit conventional time study procedures by suggesting that our samples are seldom big enough, that elimination of data because it looks out of line is not scientific, and that the elements of a time study if chosen very short are not independent and hence that methods of universal standard data have decided limitations.[2] We need statistically trained engineers to answer such objections. A new type of time study called ratio-delay is itself based on probability mathematics. In the development of time study formulas to extend time study values to conditions other than those measured, the need for statistical curve fitting and simple and multiple correlation comes up.

Similarly, other Industrial Engineering techniques can be improved by statistical analysis. (See Table II.) As the Industrial Engineer gets further into the field of methods development and from there into research, he will find that statistical techniques such as a "t-test" or "analysis of variance" can help him decide whether a new method is better than an old one, whether he has really obtained a significant difference in results. In the field of research, the Industrial Engineer will find need to get a maximum of information from minimum experimental use of operators, machines and materials, just as the agriculturalist because of long growing seasons must get a maximum of information from a small amount of data, and therefore uses statistical methods. This brings up the whole field of the mathematics of small samples and leads to the subject of the design of experiments by the use of statistical techniques. More and more, programs of the American Society for Quality Control cover subjects such as analysis of variance, to identify causes of variation which control charts can only detect; chi-square tests for significant differences between expected and observed results; and design of experiments by Latin squares. An ASQC Subcommittee on College Courses recommended one year on basic and applied, mathematically sound, statistical courses (9 quarter hours) as the eventual goal for all engineers.[3]

On the basis of all of this I believe the Industrial Engineer should "latch on" to statistical mathematics as the most productive of the mathematical fields. Industrial Engineering should become the leader in developing engi-

Table II

MATHEMATICAL TECHNIQUES USEFUL IN INDUSTRIAL ENGINEERING
GENERAL MATHEMATICS

Mathematical Techniques	Industrial Engineering Applications
Graphs and nomographs	For quick solutions and calculations in plant operations and control.
Linear functions ($y=+bx$) Exponential functions ($y=Pe^{rx}$) Power functions ($y=kx^n$) Polynomials ($y=a+bx+cx^2$)	Fitting curves to data and discovering laws or relations where one factor is related in a systematic way with another. For use in formulas for extension of time study data, equipment change-over points, variations of plant costs with output in the break-even chart, projected costs for different sizes of equipment.
	Interest or depreciation compounded continuously in engineering economy. Deterioration of warehouse material. Sinking fund depreciation. Formulas in economic lot size calculations. Budgeting variable costs.
Differentiation First derivative $=0$	Maximum or minimum points for inventory and production lot size; optimum (minimum cost) conditions of plant operation.
Second derivative $=0$	Standard deviation, at point of inflection in normal curve, the fundamental unit in quality control calculations.
Integration	Areas under normal curve in quality control; areas under mortality curves; number of standard bricks in curved furnace; voids in stored materials.
Simultaneous equations Determinants Matrixes	Economical lot size for inventories, purchases, production, where curves for fixed and variable cost conditions need to be solved simultaneously to obtain optimum values.
Computing machines Electronic computers	For quickest solution of simultaneous equations in many variables.
Punch card calculators and tabulators, such as IBM machines	Widespread plant uses for production control, inventories, personnel and cost data, wage payments, and experimental studies.
Automatic mechanical calculators	Quality control work and probability problems. Computation of standard times and other arithmetic calculations.
Differential equations	Understanding the basic operation and intrinsic errors of plant measuring instruments.
	Mortality tables for expected life of equipment, (Gompertz Law). Demand curves, such as coefficients of elasticity of demand in economics.
Theory of Games Programming Interdependent Activities	Decisions where factors are inter-related, imponderable, and involve strategy, e.g, pricing of products.
Cybernetics	Plant communications and controls.

(Table II Continued on Next Page)

[2] Adam Abruzzi, **Work Measurement**. New York: Columbia University Press, 1952.

[3] **Industrial Quality Control**, Vol. VI, No. 4, January 1950, pp. 27-30, "Statistics and Quality Control in Engineering Courses," Report of Subcommittee on College Courses, ASQC.

TABLE II (Continued)

STATISTICAL MATHEMATICS

Mathematical Techniques	Industrial Engineering Applications
Normal continuous distribution Binomial $(p+q)^n$ Poisson (limit of binomial for large n, small p).	Quality Control X and R charts for variables p charts for attributes c charts for defects, where number is very small compared with opportunity Sampling plans
Probability theory, based on above distributions, permutations, combinations, probability theorems.	
Normal distribution	Motion and Time Study Tests for whether operation and data are within control limits Determination of number of cycles to time Down time and standard times by "ratio-delay" Machine interference downtime
Confidence limits	
Probability theory	
Analysis of variance t test Correlation	Job Evaluation Differences between raters on same job Significant differences between jobs Comparing wages to point ratings
t test	Merit Rating Significant differences between supervisory ratings
Normal curve	Rating by grouping under normal curve to improve promotion, selection testing
Poisson distribution	Plant Layout and Design Number of drinking fountains, elevators, lunch room spaces for simultaneous use Roof design for expected maximum snow or wind loads Chances of peak loads for maintenance crew, power demand, materials handling equipment
Addition of variances Correlation and Regression	Estimating Precision of total estimate Relation of items Comparison of budgets and actual expenditures
t test	Significant difference between competing processes or raw materials
Addition of variances	Mating of parts—tolerance limits
	Determination of whether variance or measurements of total material shrinkage is sum of normal losses at various plant steps
Tests of Significant Difference: t test F test Chi square	Methods improvement To determine whether there is a significant difference between an old and new method
	Industrial safety Comparisons of accident records between departments, companies, or time periods
Analysis of variance	Evaluation of sources of variation, which show up in control charts or in records of safety or performances
	A powerful technique for appraising from a small amount of data what thousands of experiments would show if they followed the sample; mathematics substitutes for experience
Random block tests, Latin square, factorial experiments	Design of plant experiments and tests
Probability Theory (most useful of various mathematical tools for Operations Research). Also of importance in Theory of Games and Programming.	Operations Research Applications in industry are similar to problems involving choices between alternatives now solved by Engineering Economy and Methods Analysis, with the Industrial Engineer advising in a staff capacity for management decision.
Partial and multiple correlation and regression	Appraising quantitatively the effects of changes in variables, e.g. effect on time standards of change in size or of raw material where other factors are involved.

neering applications of it.

If this is a logical conclusion, how should the Industrial Engineering students get this training in statistical methods? All of us throughout the country have been trying out different ways to accomplish this.

Probability Theory in Basic Math Courses

One suggestion is to include more probability theory in the first two years of mathematics. The new unified math program which I mentioned will inlude not only work on the binomial theorem and the method of least squares for fitting data, but an introduction to probability and statistical methods including permutations, combinations, the normal probability curve, and correlation. I believe an introduction to these topics will get around a road block which seems to delay students in grasping probability mathematics. Elementary math courses seem to have gradually left out permutations and combinations and any other reference to the subject matter that will come up in the mathematics of statistics. Hence students have found this subject of great initial difficulty. By getting our mathematics departments to put greater emphasis on some of these introductory materials in the first two years, the students will not be unfamiliar with this subject when encountered later.

Statistics Courses for Engineers

There are three phases to this unique field of statistical mathematics, hence three "fingers in the pie."

1. *Applications* by industrial engineers in plants. (Setting up control charts, introducing sampling plans or procedures, designing plant experiments.)
2. *Statistical techniques* required for these applications (such as the normal distribution, Poisson table, correlation, t-test, F test, analysis of variance, Latin square).
3. The *mathematical basis* for these techniques (such as proofs of formulas, the derivation of the data in statistical tables, mathematical properties of the normal curve and the whole concept of probability).

In view of this three dimensional aspect of statistics for engineers, it is a knotty problem to decide who should present this subject to the undergraduate. One position we can take at the start: the engineer should teach the applications of this or any other method in engineering. The use of statistics is simply one means to an end. Departments of statistics teach the statistical techniques, but do not purport to do more than indicate how the formulas

and tables were derived. If we turn to the mathematics department, which engineering colleges have been accustomed to doing in other mathematical fields, we run into a number of problems. One is the problem which we have faced in calculus, that math departments sometimes seem to have little interest in practical examples and may confuse the student with mathematical procedures, proofs of theorems, and derivations of tables, losing the students' interest. In the case of statistics this is tragic for it is a fascinating new field for the engineer.

Problems of Presentation of Statistical Mathematics

A further problem in building this foundation of statistical mathematics for Industrial Engineers is the type of presentation. Should each formula or table be backed by rigid proof? This will indeed get into matrix theory and the geometry of hyperspace, for some of the proofs in the field of statistical mathematics are as difficult as they come. Industrial Engineering students who take statistical mathematics will find it as high level work as the mechanical or electrical or chemical engineers face in the higher math courses which they take. Mathematical statistics is not easy. So the teacher may fall back on proving the simplest case or just indicating the general nature of the proof, or he may use an analogy. The common practice is to try it out with beads. It works, therefore, it is proven. Theodore H. Brown at Harvard has developed a series of experiments to prove empirically some of the formulas used in quality control work.[4] At Tennessee we have tried to illustrate each major topic in Grant's text[5] with a laboratory experiment. (You can't believe 100% inspection isn't perfect until you actually try it.)

In view of the complicated nature of this problem, Professor Grant's text is a fine example of balance in the treatment of subject matter. It covers practical uses of statistics, development of probability theory and explanations of tables with data from bowl experiments to demonstrate and help the student understand the formulas.

Texts on quality control, however, leave out the derivation of such basic factors as the relationship of range and sigma, the familiar d_2; use of n - 1 in obtaining estimates for variances of small samples; derivation of the addition of variance theorem which is not only useful in determining practical tolerances for mating parts, but is the whole basis for the higher applications of statistics through the analysis of variance. Should not a thoroughly trained Industrial Engineer study such derivations to avoid becoming a handbook operator in the field?

Furthermore, shouldn't we think of statistical mathematics not as an area of specialization but an integral part of common core mathematics?[6] It is needed especially by Industrial Engineers but is eventually to be of use to all engineers. I believe this is in line with recommendations of the ASQC.[7] Teaching of both math and engineering needs to be reoriented.

With manifold applications of statistics ahead of us, would the engineer not be wise to turn to mathematics as the basic, first-hand source of the theory to be applied.?

The answer to the question of how much mathematics the Industrial Engineer should have, and how to present it, depends upon our concept of the Industrial Engineer and the relative emphasis on basic science and mathematics vs. applications.

I discussed this whole problem with a practicing Industrial Engineer in a metal working plant who came to us recently looking for graduates. He said, "Just teach them to add and multiply."

I next discussed it with a consulting Industrial Engineer who had recently returned from Europe, where he found that Industrial Engineers are beginning to use higher mathematics. He said, "I feel that the Industrial Engineer in the future will be using some of the computing machines and matrix algebra. I believe that he should have a thorough grounding in statistics which should be taken after he has completed his calculus and probably should take matrix algebra at the same time."[8]

Conclusions

In the light of these conflicting comments, this paper suggests the following conclusions, in summary:

1. Many opportunities exist for using mathematical analysis in Industrial Engineering. (Table II.)
2. Most of us have failed to make full use of these mathematical methods, but Industrial Engineering is not the only field which suffers from this failure. One reason for the reluctance to use mathematics by student, teacher, and plant engineer is that thorough understanding of mathematical analysis and practice in its applications are not provided in undergraduate work.
3. It is not enough to make "mere translations from a literary form of expression into symbols, without any subsequent mathematical analysis."[9] Not only economists, to whom this quotation has reference, but also Industrial Engineers in handbook style do this in such expressions as:
   $R=Y+C+E+F+M+L+T$
4. In order to bring about greater use of mathematical analysis in Industrial Engineering a firmer foundation of mathematical training needs to be provided for beginning students. One solution may be more hours devoted to the same basic mathematical subject matter. Another may be the so-called "unified" approach, which is being presented and discussed in the Mathematics Division of this conference.[10]
5. As "A Mathematics Foundation for Industrial Engineering" this paper suggests that two years of fundamental mathematics, more complete and thorough than it is now given, can provide the Industrial Engineer with many techniques which he might be encouraged to use more than he does at present. Industrial Engineering departments might develop problems and applications in I. E. courses for all of the techniques listed in Table II.
6. Expanded emphasis on fundamentals can also provide a solid foundation for advanced mathematics courses or study. If such advanced work is needed the first promising new field for Industrial Engineers is that of statistics or mathematical statistics. Other new fields like matrix algebra and symbolic logic can be investigated by gifted students through choice of electives or thesis investigations.

The purpose of this paper has been to state the problem, suggest a solution, and present information for individual decision as to what should constitute "A Mathematics Foundation for Industrial Engineering." What that decision should be, can be further tested in the light of the papers to follow on some specific examples of applications of mathematics in Industrial Engineering.[11]

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[4]Theodore H. Brown, "The Empirical Approach to the Theories of Quality Control," **Industrial Quality Control**, 7: January 1952.

[5]E. L. Grant, **Statistical Quality Control**. New York: McGraw-Hill Book Company, Inc.

[6]Everett Laitala, Correspondence dated June 4, 1952.

[7]ASQC Subcommittee, **op. cit.**

[8]Donald E. Farr, Vice President of Engineering, Methods Engineering Council.

[9]John Von Neumann, and Oskar Morgenstern, **Theory of Games and Economic Behavior**. Princeton: Princeton University Press, 1944.

[10]W. R. Van Voorhis, "An Integrated Approach to Basic Mathematics."

[11]One of the Papers referred to is presented in this issue of the **JOURNAL OF INDUSTRIAL ENGINEERING** under the title of "Statistics in Time Study." (Ed.)

A Functional Definition of Industrial Engineering

By E. Paul DeGarmo

Assistant Dean, College of Engineering, and Head of Industrial Engineering, University of California.

Many engineers, and particularly Industrial Engineers, seem to be disturbed by the fact that it is very difficult, if not impossible, to give a precise and completely satisfactory definition of Industrial Engineering. These people often seem to feel the lack of such a definition may mean that there really is no such distinct field as Industrial Engineering and that it is in reality only a branch of one of the other older and more widely recognized fields of engineering.

I have obtained considerable amusement over the years by asking anyone who questions the term Industrial Engineering to define for me the terms Mechanical Engineering, Civil Engineering, or just plain Engineering. To date, I have never received a definition for any of these for which I could not point out obvious deficiencies. For example, Webster defines Engineering as "the art and science by which the properties of matter and the sources of power in nature are made useful to man in structures, machines, and manufactured products."

I know of very few engineers or engineering educators who will accept this definition as satisfactory. In fact I know of no other definition of the term which is completely satisfactory to everyone.

If we consider the field of Mechanical Engineering we face an impossibly complex situation—yet no one seems to worry very much about the lack of a precise definition. One of my degrees is in this field but I would much rather try to define Industrial Engineering than to try to define Mechanical Engineering. Yet I believe I can give anyone a fairly good account of what Mechanical Engineers do and thus establish that their work is different from that done by engineers in the other recognized fields. However, I am very certain that I would encounter some areas of activity which I would not be able to say with certainty, were in the realm of Mechanical Engineering. For example, there is much argument as to whether hydraulics should be classified under Mechanical or Civil Engineering.

Similarily, while one may not be able to give a precise definition of Induction Engineering, one can list the functional tasks which the Industrial Engineer does and from such an analysis learn the distinguishing characteristics which set it apart from the other fields of engineering. However, it must be expected that there will be certain borderline functions, just as in the case of hydraulics.

Table I

PROBLEMS AND FIELDS OF ENGINEERING OR BUSINESS ADMINISTRATION INVOLVED IN PRODUCING A PRODUCT

Problems Involved	Fields Which Enter Into Solution
1. Selection of material	
a. Properties	Metallurgy
b. Cost	***
c. Relation to processing	***, Mechanical
2. Selection of process	***
3. Selection of tooling	
a. Types	***
b. Capacities	***
c. Design details	Mechanical
d. Types of drives	Mechanical, Electrical
4. Layout of equipment	***
5. Determination of building requirements	Civil, Architectural, ***
6. Intra-plant transportation	
a. Type	Mechanical, Electrical, ***
b. Coordination with production machines	***
7. Production planning	
a. Scheduling	Business Administration, ***
b. Control	Business Administration, ***
8. Production standards	
a. Quality	Business Administration, ***
b. Wages	Business Administration, ***

If one lists the problems which are involved in transforming an idea into a completed product, ready for use or sale, it is about as shown in the first column of Table I. It should be noted that if the world "service" is substituted for "product" essentially the same list could be used with minor modifications. In the second column of this table the fields of engineering (other than Industrial) and Business Administration are shown that normally would deal with the solution of the various indicated problems. It will be noticed that in a number of instances the symbol *** is shown instead of one of the older fields of engineering or Business Administration. This indicates one or both of two things: (a) there is little or nothing in the training of professionals in the fields indicated that fits them to solve the problem indicated, or (b) the problem usually is handled by others outside the groups indicated.

In examining Table I, one will note that the occurrence of the *** symbol is quite extensive and the problems opposite which the symbol occurs are very real and a sound solution of them is essential if economic production is to be obtained. It may also be noted that most of these problems involve a considerable amount of the human element.

Now if you will substitute the term "Industrial Engineering" for the *** symbol, wherever it appears in Table I, you will find that you have a fairly good tabulation of the functional activities of the Industrial Engineer. Thus he deals with the selection of materials and methods, the selection of equipment and the design of complex equipment groupings, the layout of equipment, the selection and basic design of plant buildings, selection and coordination of intra-plant transportation, the planning and control of production, and the setting and maintenance of production standards. These are functional activities not covered to any large degree by any other field of engineering.

Some will ask, "Don't mechanical or other engineers frequently carry out these functions?", or "Who handled these problems before Industrial Engineering came on the the scene?" The answer to the first question is that of course in some cases the problems are handled by other than Industrial Engineers. However, there are always exceptions to any rule and in most cases where other than Industrial Engineers handle these problems those doing so learn to handle only one or two of the functions and lack an over-all appreciation of the complete problem. The answer to the second question is that

(Continued on Page 24)

The Importance of Accounting in Industrial Engineering

Associate Professor of Industrial Engineering, The Pennsylvania State College

If I were the manager of any business and wanted to hire an engineer—any kind, Electrical, Industrial, Mechanical, etc.—I think I would want an answer to this question, *"Will this man be deeply conscious of the importance of costs to the success of the business?"* Would the answer be in the affirmative for most of those interviewed? I doubt it. We would probably get a lot of "lip service" to the idea, and then see these same men go off the "deep end" costwise with a lot of starry eyed ideas. I believe there are two basic reasons why this is probably true:

1. We are not developing cost consciousness through our engineering education.
2. Our graduating engineers have not achieved the management viewpoint.

The Management Viewpoint

It is of major importance that engineers achieve the management outlook. The president of a large copper company makes this interesting comment:

"More and more, those who are given the responsibility of managing local industrial plants have been the graduates of technical schools. It has been increasingly evident that a large part of the industrial leadership of the country comes from the engineer-managers who have succeeded the old owner-managers. One estimate of a large university is that 75% of the graduates of engineering colleges subsequently occupy managerial positions in industry. This is due, in part, to the fact that business is changing from the small employer-owned businesses to large businesses run by trained, salaried men, often the graduates of technical schools. In larger part, the infiltration of such men is due to the increasingly technical aspects of our modern production methods."

If our industries of the future are to be managed by engineers, many of whom will be Industrial Engineers, then a great many of these engineers will be moving into various supervisory positions in both line and staff departments on the way up the ladder to the positions of top management. Many of these young fellows will find themselves faced with problems like this:

"I am going to put you in charge of X department. If you take it, it will be up to you to get results. Our costs are entirely too high for one thing and I shall expect you to get them down. As you know, we tried two foremen in that department last year and neither has done the job. I want you to go in there and make a showing. Let's see what you can do."

You see, these engineers will inevitably be faced with the same five big problems that face any supervisor:

1. Handling personnel problems
2. Getting out the day's work on time
3. Maintaining quality standards
4. **Keeping Costs down**
5. Improving methods

Everything that they do as a supervisor falls under one of these five heads. The engineer in the supervisory capacity must have a keen insight into the techniques and importance of Cost Control and Cost Reduction if he is to discharge his responsibility as a Management Man. Is he adequately trained in the art of **"Keeping Costs down"** to be a truly effective manager of his department or area of control?

Cost Control and Cost Reduction

It is in the area of Cost Control and Cost Reduction that our Industrial Engineers should be in an especially strategic position. As pointed out in "Neuner's Cost Accounting" there are three basic aspects to accounting for costs:

1. The clerical work or cost keeping;
2. The managerial aspects, or the analytical and interpretative study of the accounting data to determine standard efficiency;
3. Systems work, or a set of rules and principles governing the installation and operation of a system through which the details of the costs incurred are ascertained.

Industrial Engineers are vitally concerned with the development of at least two of these aspects:

The Managerial Aspect

The scientific Method which is the basis of Industrial Engineering is predicated on the "determination of the standards of efficiency." If a young Industrial Engineer in charge of a department were faced with the question of, "What is wrong with department X," he would likely have to seek the answer to such further question as:

1. What about industrial relations in the department?
2. Is the department behind in production? Why so much work in process? How many days should it take to get various jobs through the department?
3. Is anything wrong with the quality as evidenced by rejects, scrap and reoperations?
4. Are costs too high as the factory manager indicated? What does "high" mean? How much can or should they be reduced? What costs are we talking about anyway?
5. Are methods in general (a) efficient? (b) up-to-date? (c) as good as can be devised?

These questions and others he would have to find the answer himself in deciding what is wrong. *All of these ought to be reflected in a single yardstick-costs.* If the company has the right kind of cost system, it should enable him to lay his finger on things he will have to go to work on in order to show results. The purpose of a cost system is not to give someone a job compiling figures, but to provide a yardstick against which to measure results obtained by the department head. But there would be no possibility of his determining what was wrong or how he could reduce costs if he did not know (1) What these costs are; (2) What affects these costs; and (3) what he can do to reduce them, and how far down they should go in order to be satisfactory.

And we must also bear in mind that this young engineer may someday in the not too distant future be in charge of a major division, plant, or staff organization with all of the executive responsibilities of top management. If his success in management is so closely inter-woven with accounting and cost procedures, what training must he have? As a minimum:

(a) Theory of general accounting
(b) Ability to analyze and interpret the financial reports, i.e. manufacturing statements, Profit and Loss and Balance Sheet.
(c) Factory Cost system and relation of factory ledger to General Accounts.
(d) Determination of Costs elements—Labor, Material and Expense.
(e) Departmental Budgets and analysis of Controllable expenses.
(f) Understand Budgetary Contriol and Standard Cost system if used by the company.

Systems Work

There will also be a group of Industrial Engineers who continue their business careers as technical specialists in Methods and Time Study, Production Planning, Materials Handling, Machine and Tool Development, etc., who will be continually concerned with the "installation and operation of systems." Some will be in various consulting capacities in which their primary concern will be the development of methods and procedures and standard practices involving paperwork handling throughout the organization. Some will find themselves in staff positions responsible for development of organization planning and control. All of these functions require a high degree of skill in paper work handling, systems, and procedures. These neces-

sitate a thorough understanding of the relationship to Cost Control and Cost Systems. They will all have a *close coordinating responsibility with the Cost Engineers and the Accounting functions of the business.* All records, forms, systems and procedures either directly or ultimately tie into the Cost finding and Accounting functions. It may be that some of the mistakes made by the engineer are due to a lack of training in paperwork procedures or to a realistic understanding of the theory and practice of accounting. It may be that the strictly "Cost Keeping" functions of accounting can be left to the accountant. The real need for understanding accounting by the engineer is well summarized in the introduction to the book "Accounting for Engineers" by Bangs and Hanselman, as follows:

"Why should engineers study Accounting? Because engineering is an important pathway to executive responsibility. When the engineer begins to assist in directing the affairs of an enterprise, whether in a major or minor capacity, an ability to read and interpret the accounts of that enterprise is of paramount importance."

Cost Consciousness

Even more important is the need for developing a *deep sense of cost consciousness* on the part of the engineer whether he is acting in a management or staff position. This is a state of mind. It is a result of straight thinking and of seeing true values in their correct perspective. We tend to ignore or resist those things we do not understand. We are likely to place little value on the importance of cost control and cost reduction if we do not understand the principles involved in accounting and cost procedures. Can we afford to have engineers going out into industry who are not fully conscious of the importance of Costs?

Recommended Accounting References

Several courses are offered in Industrial Engineeering curricula which are designed to develop a sense of cost consciousness and to promote management thinking on the importance and techniques of Cost Control. It is almost axiomatic that to achieve an understanding of the principles and techniques of accounting practices it is necessary for the student to work problems and/or complete a set of accounting books before the principles have much meaning to him. This is important to bear in mind even though one may not be training engineers for the clerical work of accounting. It is doubtful if the major objectives of cost consciousness and Cost Control are ever really achieved if engineers have not acquired a comprehensive knowledge of the technical "know how" of accounting. There is a danger in this condition, for we may "lose sight of the forest because of the trees." It is entirely possible that one may become so engrossed in the technical aspects of accounting that he would lose sight of the basic objectives. However, if proper balance between lectures and practicum is maintained the real objectives of the particular course can be kept in its correct perspective.

There are a number of good accounting books on the various aspects of Industrial Accounting. These books are applicable for accounting courses and are valuable reference for practicing engineers. It also might be suggested that a practicing engineer who wished to further his accounting education might do so by enrolling in night, extension or correspondence courses at his local university. Below are listed some suggested book references for use in several phases of Industrial Accounting:

Theory of General Accounting:
- Accounting for Engineers
  Bangs and Hanselman
  (International Textbook Company)
- Fundamentals of Accounting
  Harry W. Wade
  (John Wiley & Sons, Inc.)

Cost Accounting:
- Cost Accounting—Neuner
  (Richard D. Irwin, Inc.)
- Basic Cost Accounting—Spechtrie
  (Prentice-Hall, Inc.)

Standard Costs:
- Accounting Procedure for Standard Costs—Gillespie
  (Ronald Press)
- Basic Standard Costs
  Eric A. Cameron
  (American Institute Publishing Company)

Budgetary Control:
- Budget Principles and Procedures
  Bartizal
  (Prentice-Hall Book Company)
- Variable Budget Control—Gardner
  (McGraw-Hill Publishing Co.)
- Flexible Budgets—Williams
  (McGraw-Hill Publishing Co.)

A study of these or comparable texts through accounting courses or by home study would be of valuable assistance in furthering the management career of the Industrial Engineer.

PRESIDENT'S MESSAGE

(Continued from Page 2)

what is best for the Institute. Besides protecting its purpose, the organization itself must be protected. Purpose alone does not make an Institute. There must be a vigorous, enthusiastic, contributing, growing membership. There could be circumstances where the latter consideration would suggest broadening, changing, or perhaps to some extent, compromising the original purpose.

In addition to understanding purpose, the organization environment must be understood. Our environment is the field of Industrial Engineering. At present, it is a large, sprawling, undisciplined field. Having had no strong technical society to guide it, a certain laxness prevails. A good illustration, and of importance to this review, is use of the term *Industrial Engineer*. Much of what we believe to be an abuse of the term, is honest error. The practice was established long before the founding of the Institute and we must in justice give it fair recognition. Certain abuses, however, cannot be so excused. Traditions much older than the development of the Industrial Engineering field have given fairly well established meaning to the term "engineer." Instances where there has been a refusal to recognize this tradition are those where little consideration is deserved.

To properly promote the aims of the A.I.I.E. through a qualified membership we must somewhere set minimum standards of acceptance. Doing this, of course, bars from the Institute a number of men employed in the field, many undoubtedly bearing the title *Industrial Engineer*. Perhaps it was given to them by their employer, or perhaps it was self-assumed. In any event, the men are in the field and are identified with it. As the Institute becomes more closely associated with the field in the public mind, these men will become identified with us. Since we are thus affected, their existence must be recognized by a positive act on our part even if it be a positive act of exclusion. We should not ignore them, nor should we exclude them without carefully considering if the aims of the Institute might be more perfectly fulfilled with proper influence on the group through a close association.

After locating the dividing line created by minimum acceptance standards we must keep in mind the earlier point. The A.I.I.E. did not originate the field of Industrial Engineering and thus we may have an obligation to some honestly bearing the title but who might not meet the standards we dictate. A grandfather type clause is frequently used to make the required adjustment.

At the top of the field, in the area of highest qualification, another attention-deserving situation exists. Many Industrial Engineers are taken from formal practice in the traditional areas of the field. Their training and experience qualifies them for jobs higher in the organization. Indeed, many are taken from the field immediately upon graduation and never formally practice in it. A large percentage will fail to join the Institute or will permit their membership to lapse. Only, it seems, in the larger companies are there a

sufficient number of promotions open to Industrial Engineers to keep them in formal practice.

This top-side attrition, or skimming-from-the-top, is sufficiently prevalent to cause us to view the Institute as operating in a stratum, bounded on the bottom by our own definition and at the top by circumstance. A study of older groups to which many Industrial Engineers belong points out certain dangers in attempting to break through these barriers on any but a most clearly thought out basis. Part of the general problem here is to study and establish the area of the field in which the A.I.I.E. must operate, then to determine how it must conduct itself to operate successfully therein.

Once it has been decided from a review of the whole where we must confine our direction and what, if any, adjustments of purpose must be made to insure a vigorous successful organization we will be prepared to consider the next problem—that of expressing the specifications of the desired member in terms of the elements of experience, education, accomplishment and professional stature.

The difficulties in doing this are apparent. Few will possess generous shares of all qualifications. Most will be strong in one or two and weak in one or two. Certainly in the fringe areas where most qualification problems come to focus, there will be difficulty determining and specifying the acceptable combinations of elements.

Fortunately, other older engineering groups have experienced similar difficulties and have worked them out satisfactorily. While our problems are not identical to theirs they are not so different that we cannot advantageously follow much of their example. In fact, when we differ from their example it might be regarded as a signal to reconsider carefully the conflicting phase of our program to be certain we are progressing on firm ground.

Finally, having established qualification specifications there is the problem of applying them to specific cases. This problem is first faced by the applicant when he considers his own qualifications; then by the Chapter Qualification Committeemen and finally by the national committee. Oftentimes, to settle a question of eligibility one must go back to the original test questions:

> "Wherein lies the good of the Institute? or, How are its basic purpose and welfare best served?"

Discussion of precision in this area is futile. We are not judging machine parts or livestock. The considerations are tremendously complex but with good will, sound thought and experience as guides we can do a creditable job.

There is immediate need for work on our qualification benchmarks and this is currently receiving attention. The broader questions mentioned here are no less important but are less critical in terms of time. To act wisely when the time comes to act we should prepare now. This message is given to stimulate thought. Perhaps at the convention in May we will have accumulated enough opinions and ideas to reconfirm our present position or to decide what changes might be made to enable the Institute to better serve the profession and mankind.

THEORY OF PRODUCTION

(Continued from Page 6)

since these strategies are mutually determined. Hence, it would be more efficient in terms of utilization of their time and of efficiency in strategy determination to enforce a coalition among them under a centralized scheduler who is provided with the necessary information for strategy selection. To be effective this would require much higher speed information transmission techniques than is now typically used as well as a review of the content of the messages (information) which are now passed in order to reduce the redundancy [26] and facilitate thereby the data handling task.

A particular difficulty with expediters is that they often introduce a bias in accordance with the relative forcefulness of their respective personalities. Such bias often is inconsistent with the objective of the firm. A more logical technique would be to centralize the function of the expediters under the scheduler such that he would be required to make a rational decision of relative profitabilities of different commodities as a function of time. This would result, effectively, in requiring the scheduler or manager to consciously assign values to the constants B_i and C_i and the corresponding constants in a similar sales price function (which is concave downward about the maximum at the time desired by the purchaser). This, also, would eliminate much interpersonal friction often encountered between foremen, expediters, salesmen, and others, each of whom is urging adoption of a schedule favorable to himself and seen only from his limited prespective.

The determination of economic lot size to manufacture is now handled by a variety of formulae, each solving in some manner for an optimum between decreasing unit costs of larger lots from

". . . essential reading for every student, consultant, supervisor, or practitioner of time study."

—Journal of Industrial Engineering

WORK MEASUREMENT

NEW PRINCIPLES and PROCEDURES

ADAM ABRUZZI presents a new methodology for handling the problems of work measurement. He shows that standard data procedures currently in use are invalid (see "Developing Standard Data for Predictive Purposes," Journal of Industrial Engineering, Dec. 1952).

Dr. Abruzzi makes available objective procedures and criteria for deciding when a process is standardized and for determining when element and motion standard data have predictive value. He also shows how precise estimates and predictions can be made about the delay characteristics and the production rates of workers and operations.

WORK MEASUREMENT includes case histories that bring out the problems of application in various situations. Both theoretical and practical aspects of applied work measurement are stressed, along with potential difficulties. 25 figures and 55 tables augment the illustrations.

Suited to teaching needs, WORK MEASUREMENT also answers the problem of how to teach advanced industrial engineering students the weakness of current procedures, why they need modification, and how.

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a broader base for amortizing tooling and set-up costs and smaller lots due to decreasing costs from reduced carrying and inventory charges, etc. [21]. Each specifies a method of finding the optimum point, or lot size, between these conflicting cost trends. Actually, optima so determined are in basic error. As is seen in the model, the lot size, x'_{ijk}, is actually a function also of other variables, including the price of that commodity, the prices of other commodities, the variations in assembly cost from completing parts at times other than desired—both for that commodity and for all other commodities that may be processed, set-up costs for that commodity as well as for other commodities, the scheduled sequence of processing itself, etc. Hence, the trend reported by Moore [19] toward decreased use of economic lot sizes determined by these formulae now is explained analytically by examining in relation to the model the behaviour they induce in the prototype system when they are used.

The relationship of cost accounting philosophies and methods to scheduling is made clear by the model. The concept of marginal analysis developed by Vatter [31] for deciding whether or how a commodity should be manufactured, particularly when it does not cover depreciation charges, is made clear in relation to the model. The true objective is to maximize revenue over variable costs in the short run and to recover fixed costs, if possible, in the long. This concept is implicitly discussed by Younger and Geschlin [34] "Another problem that will arise in this (jobbing) shop is that of whether to wait for the least costly machine (to become available for work) or place the job on the machine that is virtually idle." The concept expressed by Vatter and by the Model is that whatever assignment of jobs to machine tools that maximizes net profit should be made, if the net contribution to profit from such assignment is positive (including a "goodwill' factor for customer relations). One frequent problem in this regard is that many conventional cost accountants will insist upon showing any above-standard process cost from such reassignment as a variance charged to the operating department. Such practice tends to discourage the operating personnel from seeking that schedule which is the most profitable from the point of view of the firm as a whole. This is another instance of the desirability of the coalition (in the Game Theory sense) among the operating departments under the scheduler in order to assure that local objectives will not act to restrict the net profitability of the firm as a whole.

Contributions of Other Disciplines

Until quite recently, the work of the mathematician and the mathematical economist was considered to have little relation to the phenomenal world in which the Industrial Engineer and manager must solve problems. However, these groups have proceeded at an accelerated rate toward development of techniques which now are on the threshold of practical application. Foremost among the publications in this field is *Activity Analysis of Production and Allocation*. [13]. To an Industrial Engineer, both the title and the contents may appear to be quite unrelated to their work. However, had the authors of this book been versed in the language and practice of industrial engineering it might have been entitled *Quantitative Methods of Planning and Scheduling Industrial Operations*. That is, "activities" refers essentially to productive "operations", "analysis" indicates a more sophisticated, but more powerful method of mathematical analysis than the Industrial Engineer is now accustomed to using in his problems. Similarly, the vocabulary of the text is essentially that of a mathematical economist, although the subject matter is interchangeably that of an Industrial Engineer. Linear Programming [13, Chap. 2], one of the principle models in this book, is particularly related to the problems of scheduling. In this model, "linear" refers to the assumption of linearity of output as a function of scale; "programming" is clearly analogous to scheduling: hence, linear programming means scheduling operations assumed to be represented by linear functions. When the restriction in this model that gives rise to the combinatorial problem is relaxed (i.e., $c_{ij} \leq c_{ik}$, or equivalently that only one item may be processed on a system during any given time period), it becomes essentially isomorphic to the Linear Programming Model. That Linear Programming and this model were developed independently (Linear Programming for programming activities in the U. S. Air Force and this model for industrial scheduling) indicates the large class of situations to which the method is applicable. Although Linear Programming accepts this relaxation and makes other simplifications on reality, it gains thereby a reduction in the difficulty of the computational problem. Charnes and Cooper [8] have used the Linear Programming formulation for two applications—one in petroleum refining and one in metals manufacturing—and have achieved excellent results in improving shop loading in relation to profitability in both cases.[7]

It may be expected that the use of these techniques will grow rapidly as larger numbers of firms learn of the advantages of using objective and quantitative methods in their problems and as increasing numbers of Industrial Engineers (it is hoped) become competent in the use of the modern mathematical methods.

"Operations Research" [19] is a technique first developed by scientists from various fields for analysis and decision-making in British military operations in World War II. It is gaining some notice now for its accomplishments in the application of quantitative methods to industrial situations. For example, Lathrop [14] reports certain improvements in profitability and cost of production in various instances by the use of marginal analysis techniques for inventory control. Clearly this case must have either omitted set up or subsumed it in some other manner as otherwise a production rate function with set-up ordinarily would not be differentiable. Similarly, it did not include the probability character of demand and production in the manner discussed by Dvoretzky, et al [11]. In general, operations research is a valuable technique, although it tends to be more of an ad hoc application of the scientific method to managerial problems than the development of a "science of management" in the spirit of F. W. Taylor or of *Activity Analysis* (although Taylor used what may now be termed operations research methods in many of his studies). We as Industrial Engineers and Managers would seem to be more desirous of carrying through the development of the scientific management concept and, thereby, the development of a systematic discipline and a body of knowledge such as are characteristic of our sister engineering professions.

Conclusions

This model hardly can be expected to be the final word in model building in the field of industrial engineering and management. It is intended only as a beginning, to be followed by many empirical studies seeking some optimum between difficulty of computation and fidelity of representation. As the experience gained in model building and application increases, and as the sense of the June meeting of the ASEE on the use of mathematical and statistical methods in industrial engineering permeates the field, we may expect a general leavening of the whole discipline. As we make more use of supporting disciplines, such as probability and statistics, advanced mathematical analysis, information and communication theory, game theory, servo mechanism and circuit theory, etc., in handling our problems in organization, plan-

ning, scheduling, time study, etc., we may expect a considerable reorientation of the task and methodologies of the profession. We then shall be able to distinguish more clearly between the Industrial "Engineer" and the "time-study man." As the level of quantitative rigor of our discipline is raised to that comparable with other engineering fields, the Industrial Engineer will become more truly an "engineer" and the "time study man," etc., his "draftman."

Although many sciences are held out to Industrial Engineers as the "one" which would help them most in their work, it is this writer's belief that in addition to basic engineering, mathematics offers the greatest promise to aiding industrial engineering in becoming a more scientific and analytic discipline. For example, in writing on the use of mathematics, Dadourian [10] remarks, "It has been recognized by wise men of all ages that mathematics is the most potent instrument that can be used to sharpen the mind; that it is the best means of training in analysis and synthesis (which is the Industrial Engineer's job)—that is, taking apart component elements of a problem and then reintegrating them into a new whole, and weighing the pros and cons of an issue in the scales of reason. . . ." (Remarks in parenthesis are mine.) Although many of the methods of industrial engineering analysis—such as the flow process charts, plant layout charts [4], etc., have made good use of a system of symbolic notation, this system has not met the mathematical requirements on definitions of the objects and numericization. Hence, much experience and knowledge in the use of quantitative methods have not been gained which might have been, if recent engineering and mathematical methods of analysis had been available earlier. As further a illustration, Arrow [2] presents persuasive arguments regarding the validity and superiority of mathematical analyses even in such areas as the social sciences (which include important parts of industrial engineering) where judgment, intuition, and qualitative analysis are now largely the dominant technique of analysis.

Dadourian writes further: "Mathematics is also a language. It is the most perfect and the most powerful of the languages created by man. It is a universal language; even more universal than music, which differs from country to country. When a chain of reasoning is carried out in the language of mathematics, the reasoning process becomes surer and swifter. When a law of nature is expressed in the mathematical language, it not only becomes more precise, but its hidden implications come to the surface." An illustration of this characteristic of mathematics is afforded by Clerk Maxwell's discovery which led to the development of radio, radar and television. When Maxwell expressed the experimental laws of electromagnetism in the form of the four equations named after him, he discovered the fact that electromagnetic disturbances travel with the velocity of light. This prompted Heinrich Hertz, who experimentally proved Maxwell's discovery, to exclaim, *"Mathematical equations are wiser than we!"* In fact, in building the model presented here, a similar, but humble experience was encountered. The equations were written originally to express the relationships in scheduling. However upon analyzing them, it was found that hidden implications became apparent for analysis (such as the behavior of production under priority systems, the incompleteness of "economic lot size formulae," the role of the decision-maker as a computer and data handler, the need for more adequate statistical analysis in time study and scheduling, the relationships between the theory of organization and the theory of communication and information [28], the inadequacy of the static economic theory of the firm in relation to scheduling, the relationship between production planning and inter-industry economic analysis [15], etc.) Hopefully, as the art of model building progresses and the use of Mathematics in Industrial Engineering permeates education and practice, we may proceed toward Taylor's original concepts of Scientific Management. These concepts then may be embodied in a system of principles of methodologies of the scientific methods used in the physical sciences. This then would permit us truly to say we have "scientific" management. The accomplishment of this objective is still quite distant in the future and much of the work that has been done has been, thus far, ephemeral to industrial engineering. The references in this paper are included therefore to suggest some of this work and sources of information on it. If it is to be integrated into a science of management, it must be by those engineers interested in management, i.e., by Industrial Engineers, working in cooperation with the mathematicians, statisticians, etc., as the physicist now works with these persons in handling the problems of the physical sciences.

[1] Linear programming is essentially equivalent to shop loading. The model here covers detail scheduling or shop loading accordingly as this restriction is or is not included.

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RATING EVALUATION

(Continued from Page 8)

than a similar index (.75 standard deviations) computed about the trend line; and we will therefore be conservative in stating that at least 50% of all readings will have an error from the trend line (in percent of true rating) of less than the rating accuracy index. As the trend line approaches the zero line, this conservative bias will be reduced—as is desirable. Regular practice should show a definite decrease in the rating accuracy index; practice should be continued until it reaches a point deemed satisfactorily low and then practice rating may be decreased in frequency unless the value of the rating accuracy index again grows too large.

Does this proposed technique meet the criterion of practicability? Experience in using it with typical time study men would indicate that, after some initial confusion, the method is readily accepted and used. It has further been found that, if the refinement of calculating errors in percent error rather than in percentage points is discarded (and if the range of speeds is limited to, say, from 80% to 150% this does not introduce too serious an error) the technique is readily accepted by those having extremely limited mathematical backgrounds. (To do this, line (e) on the form is omitted, and values found on line (d) are plotted directly.)

Obviously this paper leaves unsaid much that should be said about the choice of films, their use in practice, the value of the rating accuracy index that would prove satisfactory, etc. It does attempt to propose a measurement technique which offers an aid in correcting errors in trend and a measure of the errors in rating that is simple, meaningful, and useful in evaluating a training program.

SIMO ALLOWANCES

(Continued from Page 13)

(I) $M_1 > M_2$
$P_1 M_1 > P_2 M_2$

$$\text{Increase} = P_1 M_1 + (P_2 - P_1 P_2) M_2 - P_1 M_1$$
$$= P_2 M_2 - P_1 P_2 M_2$$

(II) $M_1 > M_2$
$P_1 M_1 < P_2 M_2$

$$\text{Increase} = P_1 M_1 + (P_2 - P_1 P_2) M_2 - P_2 M_2$$
$$= P_1 M_1 - P_1 P_2 M_2$$

(III) $M_1 < M_2$
$P_1 M_1 > P_2 M_2$

$$\text{Increase} = P_2 M_2 + (P_1 - P_1 P_2) M_1 - P_1 M_1$$
$$= P_2 M_2 - P_1 P_2 M_1$$

(IV) $M_1 < M_2$
$P_1 M_1 < P_2 M_2$

$$\text{Increase} = P_2 M_2 + (P_1 - P_1 P_2) M_1 - P_2 M_2$$
$$= P_1 M_1 - P_1 P_2 M_1$$

Reduction to Practice

It is obvious now that the simo allowance must compensate for the increase given in equations I, II, III and IV above. It was originally suggested that the simo allowance should be made by actual calculation using the equations. It was soon found that was too tedious for practical application.

The next idea was to select a convenient method of applying a percentage or factor for adequate compensation. The question was "How large a percentage or factor, and on what base?" Such a percentage could be based logically upon either the hand having the smallest average time or on the hand having the greatest average time.

If based upon the hand with the smallest average time, the increase ratios would be:

(V)
$M_1 > M_2$
$P_1 M_1 > P_2 M_2$
$$\frac{\text{Increase}}{P_2 M_2} = 1 - P_1$$

(VI)
$M_1 > M_2$
$P_1 M_1 < P_2 M_2$
$$\frac{\text{Increase}}{P_1 M_1} = 1 - \frac{M_2}{M_1} P_2$$

(VII)
$M_1 < M_2$
$P_1 M_1 > P_2 M_2$
$$\frac{\text{Increase}}{P_2 M_2} = 1 - \frac{M_1}{M_2} P_1$$

(VIII)
$M_1 < M_2$
$P_1 M_1 < P_2 M_2$
$$\frac{\text{Increase}}{P_1 M_1} = 1 - P_2$$

In the case where $M_1 = M_2$, the increase ratio is always equal to 1—P. If P_1 and P_2 are measured continuously from 0.0 to 1.0, then the increase ratio can range from greater than 0.0 to less than 1.0. Over a statistically large sample, the average ratio would be .50.

Where M_1 is not equal to M_2, the increase is not so easily described. But since M_2/M_1 and M_1/M_2 are both less than one, the theoretical average increase would be greater than .50.

The theoretical average increase is offset by the fact that P_1 and P_2 were not normally measured continuously from 0.0 to 1.0 (0% to 100%), but in discrete intervals, sometimes as great as 25%. A sample of 255 test calculations showed an average increase of 54% over the smallest average single hand standard element time.

At this point, it was decided to apply the simo allowance by adding 50% of the smallest variable time to each hand. This rule was observed from 1941 to 1950. In 1950, the rule was altered for further simplicity. The current practice is to add 50% of the right hand variable time to that hand and 50% of the left hand variable time to the left hand. This is a slight liberalization of the old rule and in some cases represents an excessive allowance.

Applying the rule for simo allowances to the second example of assembling switches we have the following result:

Line 2—Grasp (also Line No. 2, 3)	24 units
Line 9—Assemble (also Line Nos. 13-15)	22 units
Total Variable	.0046 min.
Simo Allowance (50% of Total Variable)	.0023
Total pick up and assemble time previously shown	.0427
Total Select Time	.0450 min.
Increase due to change in motions	.0067/.0360 = 18.6%
Increase for simo allowance	.0023/.0360 = 6.4%
Total increase due to simo operation (.0067 + .0023)/.0360	.0090/.0360 = 25.0%
Percentage of increase due to change in motions	.0067/.0090 = 74.5%
Percentage of increase due to simo allowance	.0023/.0090 = 25.5%

Tests on the actual over-payment have not yet been completed. However, there is reason to believe that the average is less than 5%. Since the variable portion of a standard element of work is usually about ¼ to ½ of the total element, the error per element would probably be less than 2½%. When the element is linked with transports, the error is reduced even further—in most cases it is believed to be less than 1%. The findings on the actual error will be the subject of a future research report.

A FUNCTIONAL DEFINITION

(Continued from Page 18)

these problems were, prior to the advent of the trained Industrial Engineer, handled by shop personnel without technical training, and still are in some cases. Many of these problems became large and important gradually over a period of years as industry became more complex. As an example, consider the case of tooling. I well recall a prominent tool engineer saying to me about ten years ago, "Tooling has got where it is today in spite of the fact that the colleges have done nothing about it—but we wish they would." Thus, as these problems became more

complex and apparent it was obvious that a brand of engineering was needed which contained basic training in fields outside those covered by the older branches of engineering. Industrial Engineering came into existence to fill this need.

A re-examination of Table I also will reveal much about the curriculum requirements for the Industrial Engineer and also why the Business Administration graduate has great difficulty competing with the Industrial Engineer. In addition to the usual chemistry, physics, graphics, mathematics, and English the Industrial Engineers needs a sound training in mechanics, engineering materials, manufacturing processes, heat-power, fluid mechanics, electrical circuits and machines, accounting and cost accounting, business organization, production planning and control, statistics and quality control, time and motion study, wage standards, toolings, psychology, engineering economy, and a heavy dose of the humanities. The problems indicated in Table I involve all of these subjects.

Anyone who is familiar with engineering curricula will note that about three-fourths of the subjects just listed are the basic ones included in all engineering curricula. At the same time the remainder are not included, as a whole, in any of the curricula except in the case of Industrial Engineering. Thus there is no doubt that Industrial Engineering is truly a field of Engineering and similarly no doubt about the fact that no other field of engineering offers the training required by the Industrial Engineer.

Similarly, examination of Table I reveals the fact that most of the problems are scarcely touched in the usual Business Administration curriculum. Thus while the B. A. graduate can cope with a few of the problems, he usually is at a great disadvantage when compared with the Industrial Engineer. The job calls for an engineer and that he is not.

Now that I have defined Industrial Engineering in terms of the functions which the Industrial Engineer deals with, I would like to give the only definition of Industrial Engineering that appeals to me:—"The broadest trained of all the engineers."

STATISTICS IN TIME STUDY

(Continued from Page 11)

a. Estimating the end-of-element watch reading prior to completion of the element.
b. Noting completion of the element and then reading the watch.

If time study men use different reading methods when observing the same element, different mean times and therefore a $\sigma_{X\text{-BAR}}$ are very possible.

On the other hand it is possible that σ_0 differs from person to person and is large in comparison to $\sigma_{X\text{-BAR}}$. If $\sigma_{X\text{-BAR}}$ is of the order .0010, the time study observer whose σ_0 is .0030 would require only about ½ as many observations for given accuracy as does the observer whose σ_0 is .0060 minutes. If this hypothesis of individual differences in σ_0 is true, why shouldn't we take advantage of this possible economy? Or to go further, why shouldn't we use such knowledge to select as time study men those applicants with the least variability?

It is possible that $\sigma_0 = \sigma_{X\text{-BAR}}$. I hope not because:

$$\text{If } \sigma_0 = \sigma_{X\text{-BAR}} = k$$
$$\sigma^2_{timing} = \sigma^2_0 + \sigma^2_{X\text{-BAR}} = k^2 + k^2$$
$$\sigma_{timing} = \sqrt{2k^2} = 1.4k$$

Eliminating either σ_0 or $\sigma_{X\text{-BAR}}$ will reduce σ_{timing} by only .4 /1.4 or about 30%.

In short, it seems to me that this paper and the experiment which produced the .008(0) minute value of σ_{timing} raise more questions than they answer. I have pointed to two of these questions:

1. How important is σ_{timing} to time study precision?
2. Have we investigated σ_{timing} sufficiently?

Until they are answered satisfactorily, conclusions based on the .008(0) figure should be hedged with repeated references to their limitations.

NOTE: Out of curiosity I am going to reanalyze Mr. Lazarus's data (which he has kindly sent to me); if watch reading error is independent of element size, I shall test the hypotheses about watch reading error outlined above and report my conclusions. This reanalysis of Mr. Lazarus's data, incidentally, should provide a check on Abruzzi's conclusion that $\sigma_{X\text{-BAR}}$ was the main source of σ_{timing} in data made available to him[7].

[7]Abruzzi, Adam, "Work Measurement," Columbia University Press, New York, 1952, page 233.

Book Review

Timestudy Fundamentals for Foremen

By Phil Carroll, Professional Engineer, McGraw-Hill Book Company, Inc., 1951, 209 pages.

—Reviewed by Joseph S. Dwyer, Professor and Head, Department of Industrial Engineering and Engineering Drawing, Texas Technological College.

As viewed by a foreman, time study may have a special meaning entirely different than that of the time study man. The importance of the time study function and wage incentive procedures are not always fully understood by the foreman. For the average foreman, existing time study texts and literature are not apt to be a good source of information because of the difference in viewpoint. "Timestudy Fundamentals for Foremen" by Phil Carroll has been written to provide information specifically for the foreman in language he can understand. Since the book is directed toward the foreman and not the Industrial Engineer, the relationship of time study to the foreman's position is given first consideration. The popular first edition and the recently published second edition concentrate on selling time study, methods analysis, and wage incentives to the foreman. It also gives the basic information the foreman should know about these things. For the most part, Mr. Carroll sticks to the selling and informative objective. However, there are frequent pleas for cooperation and understanding between the foreman and time study man.

Mr. Carroll uses an informal conversational style of writing in which the discussion is directed in a personal manner toward the reader. Shop slang and terms are used generously. The numerous illustrations and cartoons emphasize the main points. The book is fast and easy to read. It is well suited for use as a manual for group training and discussions.

For the diligent foreman or individual who wishes to make a careful study of time study, the presentation might be unsatisfactory and the style objectionable because of the "talking-down-to-the-reader" impression that it gives, the repetition, and the expression of opinions which are presented as facts. Since the book was not written for such a reader, however, such devices may be justified.

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Book Review

Methods of Operations Research

By Philip M. Morse and George E. Kimball, The Technology Press of Massachusetts Institute of Technology and John Wiley & Sons, Inc., New York, 1951, 158 pages.

—Reviewed by Robert M. Eastman, School of Industrial Engineering, Georgia Institute of Technology.

Operations research has been hailed by many as a great discovery for solving practical problems. Others regard it as a publicity man's treatment of the scientific method. In this volume, the authors describe operations research by discussing its wartime organization and performance. Examples from their World War II work with the Navy skillfully supplement the statements of general principles.

The major contribution of operations research is, I believe, its organization of scientific method and manpower for the solution of the practical problems of business, industry, government and the military: It is true that OR presents little or nothing new in scientific theory or knowledge. However, OR has pointed out how an organization may apply pure science and its methods to the solution of ordinary operational problems. OR has also helped break down the interdisciplinary barriers resulting from overspecialization. Outstanding results have been obtained by groups of scientists from different fields.

The industrial engineer will be interested in the organizational aspects and the scientific procedures. Although most of the examples are military, many of the ideas and procedures can be used in industrial work.

The average industrial engineer may find the mathematics a little difficult. He can still follow the descriptive material. Moreover, the profession of industrial engineering is using more and higher mathematics as it is called upon to produce scientific justification for its practices. This trend has been pioneered by the industrial engineering departments of our universities. Greater use of the scientific approach, including operations research organization and techniques, will benefit the profession by putting it on a far firmer foundation.

The Industrial Engineer in Purchasing

By George E. Hecox

Professional Engineer

The future expansion of engineering into new fields depends largely upon the imagination of industrial management and their ability to recognize the versatility of the engineer in departments other than design. Production engineering, incentives, systems, and job simplification are some of the areas that have been penetrated by engineers and now are included in a group known as Industrial Engineers. More recently Purchasing has provided another berth for our profession. In the May 26, 1952 issue of the "Wall Street Journal," Mr. Joseph M. Guilfoyle wrote an article on "Cost Control," in which he demonstrated how General Electric has cut costs by turning their engineers loose in their purchasing department.

The engineer is at home in the Purchasing Department. Why should design engineers spend their valuable time re-interviewing the multitude of salesmen that a buyer might pass on to them, just because he doesn't know if the item is of use or not? An engineer in the buyers seat can quickly ascertain what materials and processes can be utilized by the designer or development engineer and then forward these persons, or the information they have to offer, to the proper authority.

The purchasing department usually reports to an authority who is responsible for profits, such as the comptroller. Their primary purpose is to purchase a specified material, of the best quality, at the least unit costs. They are responsible for financial solvency, maintainance of production schedules, and sales at a competitive price with reasonable delivery.

Their financial responsibility is obvious; they must obtain "the bestest for the leastest." The responsibility to production departments is just as important, especially in periods of scarcity. (This scarcity can be in material, as during a national emergency; or a scarcity of capital, as during an economic recession.)

In a national emergency the buyer must be able to purchase raw materials to keep the machinery operating and producing goods. He must be able to say at a glance whether a material specification is satisfactory, or if the analysis of an offering of steel will provide the product with the strength required. Who can determine such things better and faster than an engineer? Who will be most capable of recognizing materials that will be better than those presently used? The answer is so obvious that until recent years it has been generally overlooked.

In an economic recession or a highly competitive period the price of the article is extremely important. The purchasing department must be able to analyse the parts that go into the making of a product and find ways of purchasing these items for a smaller unit cost, yet not affect the quality of the end product. True, this is done by the product designers who see some of the new techniques, but who is in a better position to keep ahead of the trends, to visualize the application of the materials the salesman offers, or note how other manufacturers are doing things? Yes, an engineer in purchasing can hold a very strategic position.

To what extent does the purchasing department affect sales? Each vendor is a potential salesman for the products of their customer. As an example, let us use pneumatic tools. Mr. "A" is a salesman for a manufacturer of fasteners. He remarks, "I'm having a rough time sellings screws to the B. and A. Manufacturing Co., because they think there should be a faster way of assembling parts." Here, the buyer retorts, "Don't they use pneumatic screwdrivers?" Being a good salesman Mr. "A" rushes right back to B. and A. and sells them a million screws because he has found a faster method of using them. In the meantime the airtool manufacturer has sold some air powered screwdrivers.

Who knows the methods applications of a companies' products better than the engineer working in that company? Who has the opportunity to advertise the versatility of your product better than the buyer? Many salesmen are engineers and an engineer talking to an engineer, is like pulling the plug on a reservoir, a wealth of information is always released. Yes, an engineer can do a great deal in purchasing.

These thoughts are being presented in the hope that more people will recognize the future that is ahead for the "Purchasing Engineer"; here is a man the stockholders can point to with pride and say, "There's an individual that will help us get the highest possible return on our investment."

Book Review

Factory Planning and Plant Layout

By William Grant Ireson Prentice-Hall, Inc., 1952

—Reviewed by W. A. Brooks, School of Industrial Engineering, Georgia Institute of Technology.

The subject book contains a total of 312 pages of text, plus 46 pages of problems and templates necessary thereto and 16 pages of appendices containing Capital Recovery Factors, Present Worth Factors, both single payment and uniform annual series, and certain data for factory planning. The text is divided into thirteen chapters. The chapters are in general well arranged and complete, with a minimum of extraneous matter, and follow a logical sequence, except for that on Economic Analysis (Chapter 3), which it is considered could have more appropriately been made the last chapter. The chapters headed Introduction to Factory Planning (Chapter 1), Common Errors in Layout (Chapter 6),

Layout of Auxiliary Departments (Chapter 7) and Management Aspect of Factory Planning (Chapter 13) were considered to be especially good. Chapter 10, Factory Services, while very complete, at times goes into too much detail, as for example the explanation of what is a watt. The same can be said with more emphasis about Chapter 12, Planning Personnel Facilities. It is difficult to see the need for an explanation of the steps in hiring a man, how to run a cafeteria or what causes sweat. But these are minor faults and do not particularly harm the book—they just seem out of place.

The book is amply illustrated, particularly in connection with Materials Handling. The problems are valuable if the time available permits the instructor to proceed in a leisurely fashion and assign the problems as a build-up to the problem of a complete factory layout, but in any case they cannot be considered a detriment. The compound-interest tables are helpful, as are also the data on Materials Handling, Clearances for Washroom Facilities and Minimum Fixture Requirements.

Lighting, heating and ventilating are touched upon in a few scattered spots in the book, but it is felt that these important characteristics deserve more extended treatment, and that a chapter on natural and artificial lighting and another on heating and ventilating would have added materially to the completeness of the text. However, it should be noted that most authors on the subject of factory planning and plant layout also fail to discuss these factors. And it is also felt that, although the author appears to be cost conscious, he could well have collected in one place all the various items which go into the cost of the finished product.

Along this same line, it is believed that one criticism which can justifiably be made of the book is that, while it frequently enumerates a list of characteristics, advantages, disadvantages or points in question, these are usually buried in the text, making them hard to find and difficult for the student to recognize as important points. Such matters should be tabulated and inset to emphasize their importance, and to make them apparent for ready reference.

Summing up, the writer feels that the text is well arranged, well written and reasonably complete. It is well suited for use as a college text.

Book Review

A Manual For Time Study Supervisors

By Robert L. Thomas, Columbia Graphics, Columbia, Conn., 1952, 66 pages, $2.00.

—Reviewed by Robert M. Eastman, School of Industrial Engineering, Georgia Institute of Technology.

This small volume is a distillation of customary ideas and procedures used in time and motion study. It appears to be based on a successful company manual. However, someone who wants a short but fairly complete summary of time and methods study will find this book interesting and useful.

Book Review

The Fundamentals of Top Management

By Ralph Currier Davis, Harper & Brothers, New York, 1951, 825 pages, $6.00.

—Reviewed by Robert M. Eastman, School of Industrial Engineering, Georgia Institute of Technology.

As an Industrial Engineer is promoted upward in his company, he more frequently is confronted with management and organizational problems. Further progress depends on his managerial ability although he will always use the logical approach of the engineering method.

Since Prof. Davis reached his present eminence via the engineering college-Industrial Engineering route, his approach will appeal to Industrial Engineering thinking. His treatment of policy, philosophy and theory are quite thorough.

Unfortunately, the book is handbook length, but not handbook organization. The discussion is abstract with too few examples to relieve and illustrate. Prof. Davis's material is accurate, authoritative and sound, but it is a formidable work to anyone except a determined reader.

Finally, can management be taught in a class or learned from a book? As John McDonald points out in the December 1952 issue of Fortune, getting, giving and withholding information is the crux of many management decisions. The evaluation of available data and estimation of vital but missing facts are essential to executive action. All any book can do is to outline successful policies and theory and to give examples which may supplement experience.

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